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AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
L. G. HANSCOM FIELD, BEDFORD, MASSACHUSETTS

Earth Science Applied to Military Use of Natural Terrain

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Abstract

A survey of the state-of-the-art in the evaluation of natural terrain by earth-science techniques and measurement systems is presented in response to a need that existed for many years. This report considers the terrain as an envelope of the environment and all related parameters that are basic in an evaluation for relevant military applications such as unimproved landing areas, trafficability, site selection for operational facilities, terrain reconnaissance and surveillance, and target detection within a masked terrain complex. Methods of terrain-data acquisition, analysis, and evaluation and their limitations are reviewed. The status of research and development, specifying the gaps in technology, is summarized with accompanying conclusions. The report forecasts the requirement for an automated terrain-data acquisition, storage, and display system. Recommendations are suggested for further investigation to advance technology that will provide quantitative terrain factor values. A simplified matrix method of digitizing terrain data is described in the appendix as a necessary intermediate step to the computerization of pertinent data. Information pertaining to the classification of terrain data, field devices to measure bearing strength, and a visualized optimum remote sensing system is also given in the appendix. A glossary and a comprehensive bibliography are included.

Preface

Reliable methods for predicting terrain conditions on a quantitative basis are vital in the planning of military operations. In the past an equilibrium was maintained regarding terrain-classification and weapon-system capabilities, but recent and rapid advances in weapon-system technology have made present terrain-classification methods inadequate.

Chapter I (Introduction) of this report describes the problem and delineates the need for terrain information. Methods of analysis and performance prediction of military activity by considering the terrain parameters, criteria, and environmental effects on the proposed activities are contained in Chapter II.

Chapter III on Remote Sensing is a summary of airborne sensing methods used for rapidly obtaining terrain and related scientific data over vast areas of the world. This chapter also introduces the concept of incorporating all types of sensors into systems that would produce imagery depicting the properties of different terrain.

Terrain utilization is discussed in Chapter IV. Many of the applications demonstrate the value of applied geoscientific analysis and evaluation for superior terrain-engineering planning.

Research and development to improve non-contact sensing technology is discussed in Chapter V. Gaps in the science and methodology and the status of present objectives are summarized. Some of these objectives are site selection, determination of aircraft trafficability on natural surfaces, development of analytical techniques, and evaluation of the effects of climate and weather on materials and terrain conditions.

Conclusions and Recommendations in Chapter VI identify the gaps in the knowledge of techniques for terrain utilization, and suggest areas warranting further research to develop a capability for acquiring and using data in a faster response to existing technological and operational needs.

A Glossary of earth-sciences terminology is included for the benefit and quick reference of the lay reader. The References and Bibliography contain selected material from the voluminous literature of the scientific and engineering community.

The Appendices present detailed information to supplement the material in the body of the report.

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EARTH SCIENCE APPLIED TO MILITARY USE OF NATURAL TERRAIN

I. Introduction

1. PURPOSE

The utilization of earth-science technology in determining the potential of practical military use of natural terrain could greatly enhance the global mobility of our military forces. The purpose of this report is to delineate these techniques to scientific, engineering, and military interests, and to present salient background information for use in further research or terrain appreciation. The contents may be used for specialized training programs, guidance in planning, engineering needs, and strategic and tactical situations.

2. SCOPE

This report presents significant information, with pertinent references, on the properties of natural terrain. It defines terrain and its primary parameters; evaluates methods of analysis and data-acquisition techniques; surveys the research and development status of science and technology pertinent to the solution of military environmental problems; and points out the deficiencies in our present knowledge. The report also recommends programs to eliminate many of the limitations in our earth-science technology, with emphasis on non-contact sensing of terrain.

(Received for publication 23 July 1969)

3. STATEMENT OF THE PROBLEM

The military concept of maintaining global capability requires sufficient and precise information on terrain and related environmental conditions. The records reflect many instances where the lack of proper and timely information resulted in critical loss of time, life, material, and tactical superiority. These include problems primarily in vehicle and aircraft trafficability, shore landings, and the construction of installations.

These problems are adequately summarized by the following quotation of Lt. General William B. Bunker, USA, Former Deputy Commanding General of the Army Material Command: "Mother Nature, in the guise of swamps, mountains and deserts or as blizzards, fogs, and blinding heat is the true immobilizer of armies."

Since time immemorial, commanders have sought an army that could move in concert-combat, tactical support, and administrative elements-over the same terrain and at the same speed. This challenge is not always met successfully when operating in complex terrain.

The lack of terrain data for large areas of the world is a serious handicap. The primary sources of information (reports, maps, photographic documentations, etc.) are inadequate for producing necessary detailed data. Subtle conditions of the terrain complex cannot be estimated from small-scale maps or from data in the inventory that are not suitable for efficient use by performance-prediction models. Rapid non-contact measurement techniques of terrain parameters are only supplementing, not replacing, the standard, slower, ground sampling and testing methods.

The classification of terrain for analogous studies is difficult even in well mapped areas of the world. The formulas for direct comparison of terrain parameters of construction materials; surface roughness; temperature and moisture content as a function of climate and weather; drainage and water supplies; vegetative cover; horizontal and vertical distribution of surficial materials; and the nature of underlying geologic formations are based on proper data acquisition.

Today, planners, strategists, and operations analysts are frequently forced to use information that limits their decisions to the generalized rather than specific effects of terrain on the various military activities. However, today, a delay of an hour or the incapacitation of a portion of the tactical force through an unanticipated environmental or terrain condition could comprise the difference between defeat and victory.

4. NEED FOR TERRAIN INFORMATION

Since man's activities are predominantly terrestrial, they are largely dependent on his efficient use of the natural environment. In the past, he operated on a

theory of superabundance of resources in the environment. It was assumed that his world contained unlimited areas in which to expand, resources to exploit, water to use or pollute, and time to plan for the future. There is now the sudden realization that these assumptions are not true; man must now economize his natural resources and use his manpower, equipment, and terrain more efficiently.

To fully utilize the environment, it is necessary to know the properties of the earth. This knowledge can only be gained by new scientific techniques. New instrumentation is required to permit rapid data acquisition by automated methodology.

Tactical requirements dictate the precise location of operations. The military need for terrain information is usually implicit, and not specified in the official requirements; however, it should be a prerequisite in the evaluation of any prototype weapon or proposed plan.

Pertinent terrain information is vitally necessary for tactical maneuver of ground forces, battle planning, aircraft navigation, target location and analysis, site selection of bases and airfields, strategic planning, and other uses. However, the acquisition of this information is frequently assigned a relatively low priority, and data needs are often obscured by the system approach to weapons development (Sturm, 1967).

1.1 Historical Review

From the time of Homer in 900 BC, the concern for the knowledge of terrain in the form of myth and legend has been described in the records of military campaigns. In the 16th century, Niccolo Machiavelli wrote:

> ". . . .and meanwhile learn the nature of the land, how steep the mountains are, how the valleys debouch, where the plains lie, and understand the nature of rivers and swamps. To all this he (the prince) should devote great attention. This knowledge is useful in two ways. In the first place, one learns to know one's country, and can the better see how to defend it. Then by means of the knowledge and experience gained in one locality, one can easily understand any other than it may be necessary to observe; for the hills and valleys, plains and rivers of Tuscany, for instance, have a certain resemblance to those of other provinces, so that from a knowledge of the country in one province one can easily arrive at a knowledge of others. And that prince who is lacking in this skill is wanting in the first essentials of a leader; for it is this which teaches how to find the enemy, take up quarters, lead armies, plan battles and lay siege to towns with advantage" (Machiavelli, The Prince, Florence, 1513).

History has not changed the basic concepts of land warfare. Although methods of warfare have become more sophisticated, the objective is still to dominate the territory of the enemy and destroy his will to fight.

The major contributions of earth science applied to the art of warfare have been in cartography, geography, military geology, and engineering.

4.1.1 CARTOGRAPHY

Maps were first developed about 900 BC as a guide to explore the earth's surface. The great conquerors of ancient and medieval time used crude maps in planning and conducting their campaigns. Throughout history, military conquest has stimulated mapmaking and aided science. By 150 BC, cartography combined the achievements of the scientist with those of the explorer and surveyor in presenting a picture of the physical characteristics of the earth's surface. Maps and charts developed into a major source of information for military purposes in the last half of the nineteenth century (Lobeck and Tellington, 1944, p. 1).

4.1.2 GEOGRAPHY

Aristotle founded scientific geography about 350 BC. Mapmaking and later exploration furthered the progress of advancing geographic knowledge until the first modern world atlas was published by Ortelius in 1570. The knowledge of world geography was increasing by the early 1900's, with the exception of the more remote regions (Strahler, 1963, p. 7).

4.1.3 MILITARY GEOLOGY

Terrain features have been used to the disadvantage of enemy forces since 900 BC. In 1826, geology was first applied to warfare in Germany, followed by the U. S. Civil War in 1864–although a number of isolated examples occurred in earlier history when rivers were diverted or mined in war. The first American military geologist advised the U. S. Army on varied terrain problems during the war in the Phillippines in 1899. Many countries expanded their interest and application of military geology in the 1930's. The large military organization added a staff of geologists, geographers, and related skills to assist in the planning and conduct of their operations (Erdmann, 1943, p. 1177).

4.1.4 ENGINEERING

Since the first fortifications were designed and constructed in early history, engineering units assigned to all military organizations have been delegated the responsibility to overcome terrain hazards and erect structures to enable the troops and weaponry to combat the enemy more effectively. Such structures were roads, tunnels, bridges, fortifications, gun emplacements, airfields, and dams. Indigenous construction materials were used by developed resourcefulness. Mobile warfare introduced many new problems for engineering ingenuity to provide the required construction, repair, maintenance, and logistic support, particularly in large scale operations (Erdmann, 1943, p. 1176; U. S. Geological Survey, 1945).

1.2 Modern Technology

As war became more complex, the size and range of artillery, missiles, and small-arms fire expanded. The airplane introduced problems of air navigation and precision targeting and bombing. Aerial reconnaissance furnished a fast and easy means of obtaining timely information concerning terrain and the enemy's movements and methods of attack.

With the advent of mechanized warfare in World War I, and improved capability of aircraft and ground forces in World War II, the tactical use of terrain became more critical. Science and engineering developed the means to surmount the major obstacles and minimize the hazards.

The progress made in photo-mapping techniques since the mid-1940's has been phenomenal. The aerial camera has developed as one of the primary surveying instruments. Topographic maps and photographs have been the main source of information in the appraisal of terrain and environmental effects. Supplementary data were added by studying recent large-scale geologic, soils, climatological, and vegetation maps. The introduction of terrain models and diagrams reconstructed from maps and photographs was accepted as a standard procedure for showing details in realistic perspective to the military leaders (Coleman and Lundahl, 1948, p. 453).

Since World War II, the military has used earth scientists and engineers in collaboration with intelligence groups to solve problems relative to military use of terrain. The rapid solutions to terrain problems, the preparation of special maps, and the provision of other requested data to forward combat organizations by these men received widespread praise for their accuracy and value (Committee on Geophysics and Geography, 1953, p. 7).

Present research is developing methods of remote sensing from aircraft and extending such a capability to satellite altitudes. These methods will provide knowledge of global terrain to predict performance of pre-planned activities. Refinement of differentiated signals from active and passive sensors is improving the identification of all natural materials and their properties in a suitable display for efficient system interrogation.

Current technology permits (1) the selection of landforms to support aircraft operations; (2) the identification of areas possessing weak natural materials or structures susceptible to natural or induced landslides; (3) detection of disturbed foliage, vegetation, or other terrain parameters that could provide enemy camouflage; (4) determination of the hazards of ice and snow surfaces and permanently frozen ground features; (5) the location of natural drainage hazards, impassable routes due to flooding or damage; and (6) assessing site stability and the potential occurrance of disasters from catastrophic forces (Van Lopik, 1962, p. 776).

Earth-orbiting surveys, utilizing photographic sensors, offer a unique system for producing topographic and geologic maps. Maps at 1:1,000,000 or smaller could be produced from such data on a global basis. Although much of the surface mapped at 1:1,000,000 needs revision, it would be impractical to complete world-wide mapping at this scale or larger except by orbital remote sensing (Carr and Van Lopik, 1962, p. 6).

An airborne and orbital system would enable the transformation of all map, photo, and quantitized terrain data into digitized form at data bank centers for transmission to forward military units in a matter of minutes to hours. The convenience and versatility of aerial and orbital surveying, mapping, and sensing methods have only commenced to be exploited for use in modern warfare (Mays, Noma, and Aumen, 1965, p. 19).

5. PREVIOUS WORK

Since 1935, U. S. and foreign civilian and military agencies, universities, private companies, and research institutions have conducted intensive studies to develop methods for predicting terrain conditions for military, scientific, and commercial use. The primary federal agencies engaged in research on terrain problems are discussed in Appendix A.

The bibliographic references on the subject indicate the wide range of topical and geographical coverage and gaps in information. Many organizations concentrated on some of these gaps in response to military needs. Recent emphasis has been centered on the classification of terrain parameters from the interpretation of remote sensor data.

Since its founding in 1879, the U. S. Geological Survey (U.S.G.S.) has been one of the leading non-military federal organizations in the scientific study of the earth and use of terrain for military and civilian purposes. For over 150 years, the U. S. Coast and Geodetic Survey (USC&GS) has been making precise measurements of the earth and its waters. Many State agencies have been using earth science and related technology in the construction of airfields, roads, highways, waterways, and installations. State governments also participated jointly with federal agencies in the long-term mapping and locating of natural resources.

5.1 Department of Defense

Since World War II, over 37 DoD agencies have been involved in area analysis, environmental research, and programs related to terrain. Their common objective is to obtain knowledge of the physical and cultural environment in all parts of the world. Of the agencies involved, 13 are in the Air Force, 16 in the Army, and 8 in

the Navy, Advanced Research Project Agency, and Defense Intelligence Agency (DIA). The description of their work pertaining to terrain is beyond the scope of this report. See Appendix A for additional information.

5.2 Other Government Agencies

Eighteen other research groups are distributed largely among the Dept. of Interior, Dept. of Commerce, Dept. of Agriculture, Atomic Energy Commission (AEC), National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), and the Dept. of Health, Education and Welfare. These agencies have been performing major efforts in environmental research and testing. DoD has frequently utilized their services.

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II. Terrain Study, Analysis, and Evaluation

1. INTRODUCTION

A study of the natural environment necessitates dividing the total complex into its separate parts. One of these parts–terrain–is as an aggregate of all physical and man-made features of an area. This aggregate includes an exclusive group of primary and secondary factors that characterize specific attributes of the terrain (AFM 88-53, p. 146).

The primary factors are: surface geometry and landforms, composition and engineering properties, vegetation, and hydrology.

The secondary factors are: cultural features and climate and weather.

Different combinations of terrain factors can have similar effects on some of man's surficial activities and have a varying impact on others. Terrain factors do not have permanent critical values for all types of activities. In many cases, a critical value (the point beyond which the activity cannot be satisfactorily performed) will change if it is even slightly modified in form, weight, etc. (Carr and Van Lopik, 1962, p. 3).

Terrain assessment by genetic and physical-attribute examinations can provide reliable information; such information, derived from contact, non-contact, and indirect methods, yields valuable performance-prediction data.

Present methods correlate field-test data and supplementary sources with analagous terrain areas, but most of the available global information is qualitative, not quantitative as desired. At best, the qualitative genetic approach is merely a substitute for detailed, directly measured terrain data (AFM 88-53, p. 124).

2. REGIONAL AND ENVIRONMENTAL ASPECTS

A knowledge of regional information is a necessary background to understanding and analyzing geologic, soil, vegetation, and implied engineering conditions. The characteristics of the local terrain in factor classes (a specific category within a terrain factor) are then determined. A comparison of the features in the region with the local complex reveals facts on materials and their surface and subsurface properties. Landforms, drainage and erosion patterns, and vegetation which can be identified are correlated with features which cannot be directly observed (Belcher, 1948).

Environmental conditions directly affect the existence, development, and alteration of terrain characteristics. The formation and sculpturing of landforms are controlled by the decay of rocks at the surface, the nature of the underground geology, the degree of weathering action, and the influence of the climate. An uneven surface is the result of etching by agents of denudation or deposition of transported materials. Thick, well-bonded-type rocks resist erosion and remain as hills, while the weaker materials form valleys. Running water transports soil and broken material, and the rock waste carried by the water scour and modify stream and river beds. Gravity and wind are other forces which remove material. Along the coastlines, waves undercut cliffs and blocks of rock fall into the sea. Waves batter the fallen blocks into sand, and the tides carry away the sand.

Soil is formed from rock wastes, shattered minerals, and organic matter. It comprises the outermost layer of the earth's crust, and its profile includes the decaying remains of plants and animals, a wealth of living organisms, the roots of living plants, and bacteria.

The environmental temperature and the composition of the rocks in an area determine the character of the soil in that area. Rock wastage is removed unless the climate is conducive to the growth of vegetation that binds the materials in the soil. Removal of vegetation can result in rapid soil loss, and glaciation can completely strip a region of all its soil (Thornbury, 1954, p. 68).

3. TERRAIN CLASSIFICATION AND METHODS OF ANALYSIS

3.1 Classification

In the classification of terrain, the characteristics are described in subjective and objective terms, and data on landform, microrelief, soils, rock, drainage, vegetation, and related properties are incorporated.

The current technology is limited in the quantitative classification of terrain properties for determining the critical values in terms of their effect upon specific military activities. Expedient classifications of the terrain components, based on data obtained from field observations and laboratory analysis, are largely qualitative on individual factors (Carr and Van Lopik, 1962, p. 2).

Qualitatively described terrain with a few measured factor values can provide an index of the regional terrain. Classification by this method is rated on a valid universality of application, degree of simplicity of measurements, repeatability of factor values, mappability or portrayability of data produced by other techniques, and completeness of data.

The most accurate appreciation of terrain is obtained by scientific analysis of the data and a determination of terrain-factor effects on activities. The primary categories used to describe terrain follow.

3.1.1 SURFACE GEOMETRY

Surface geometry is the measurement of the physical forms of features constituting the earth's surface. The basic components can be measured as slope, relief, distribution of topographic highs and lows, plan and profile configurations, and related dimensions.

Landforms that are primary surface features have varying external and internal characteristics, are in various stages of development, and change with environmental conditions. The major landforms are the plains, plateaus, hills and mountains. The secondary features are cliffs, valleys, lakebeds (playas), and alluvial fans (Leet and Judson, 1967).

Landform classification commonly utilized is based upon differences and similarities resulting from variations in the local relief and in the amount of land in slope. Mountains and hills have most of their land in slope and have moderate to high relief while plains and plateaus have surfaces that are predominantly level or gently sloping and have low relief.

There is great diversity in the surface features of the four major types of landforms, and differences within each type result from varied conditions that caused the formation of the original surfaces, the weathering and erosion that have been present, and the variations in slope and local relief.

3.1.2 COMPOSITION AND ENGINEERING PROPERTIES OF TERRAIN

The terrain is a reflection of the surficial (unconsolidated) materials and bedrock (consolidated) materials in an area. Since military operations are dependent upon the characteristics of the unconsolidated portion, that portion is emphasized in this report.

The entire thickness of unconsolidated material overlying the bedrock is considered to be soil. It varies in definition by geologists, agricultural engineers, construction engineers, soil scientists, and others. Several systems of classification are commonly used, based on characteristics and uses (See Figure B-1 in Appendix B).

3.1.2.1 Soil Properties

The properties of soil vary with its grain size, structure, moisture content, color, vertical position in a series of distinct layers in the profile, and geographical location. Soil is usually a mixture of varying proportions of particles of different sizes. Each component contributes its characteristics and properties to the composite mixture.

(1) Profile

Many processes of formation occur as soil is formed from disintegrated particles of the earth's crust or parent material. Air and water enter the spaces between the particles, organic matter mixes with the particles, and the soil-formation process begins. Definite layers develop near the earth's surface, and these layers (horizons) differ chemically and physically. A vertical cross-section of these horizons constitutes the soil profile (Figure 1).

From the surface downward, four horizons are recognized and are identified by the letters A, B, C, and D. The upper layer, or A-horizon, is the zone where organic matter accumulates on the surface and where the semi-decayed plant and animal material or humus is found. This is the layer from which water soaking into the ground may remove material by either chemical or physical action. The B-horizon, the second layer, is the zone where material removed from above accumulates. It is usually composed of finer particles and forms a more compact substance than the layer above. The C-horizon consists of broken-up fragments of the parent material. The D-horizon is the underlying, unaltered parent material. Figure 1 compares a typical pedological soil profile with an engineering profile.

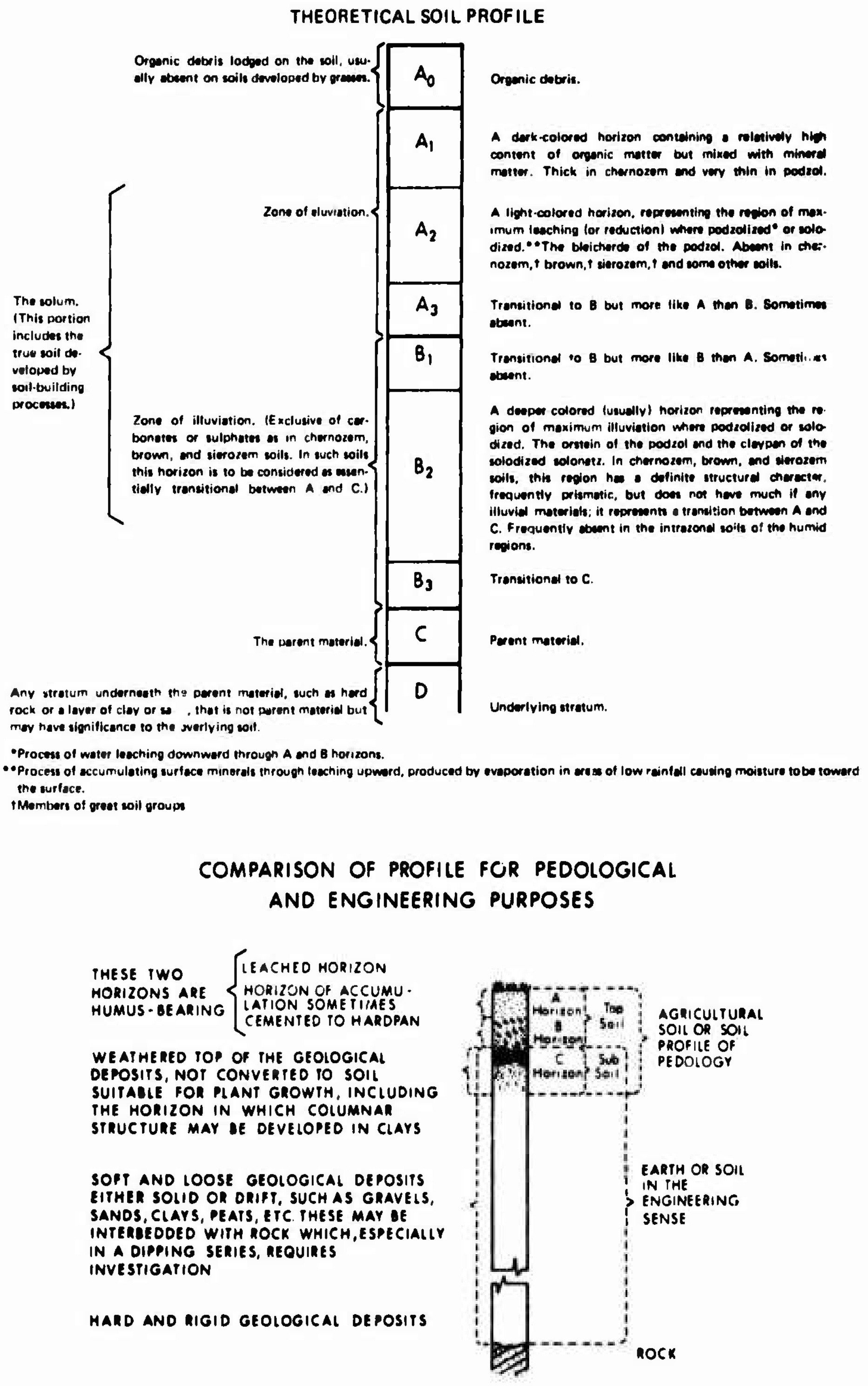


Figure 1. Soil Profile With all Horizons Present for Pedological or Engineering Interpretation

A typical profile is shown as follows:

Horizon	Thickness	Range	Term
A	10-12 In.	2 In. -4 Ft	Topsoil
B	10-12 In.	4 In. -8 Ft	Subsoil
C	Variable	Variable	Mother Soil or Parent Material in Broken Fragments
D	Variable	Variable	Underlying, Unaltered Rock Stratum

(2) Texture

The texture of a soil determines its ability to absorb water, heat, and air and its amenability to plant growth. The texture of a soil reflects the predominance of one size of particle or composite mixture of sizes imparting its peculiar properties. The common classes of texture are sand, silt, and clay that vary in size from diameters of 1 mm in coarse sands to a fraction of a millimeter in clays, as seen in Figure 2. Soils may include particles of organic matter.

Individual grains of sand can be distinguished, and they feel gritty to the fingers. Silt particles are difficult to observe, but they feel and look like flour. Clay particles cannot be seen without a microscope.

(3) Structure

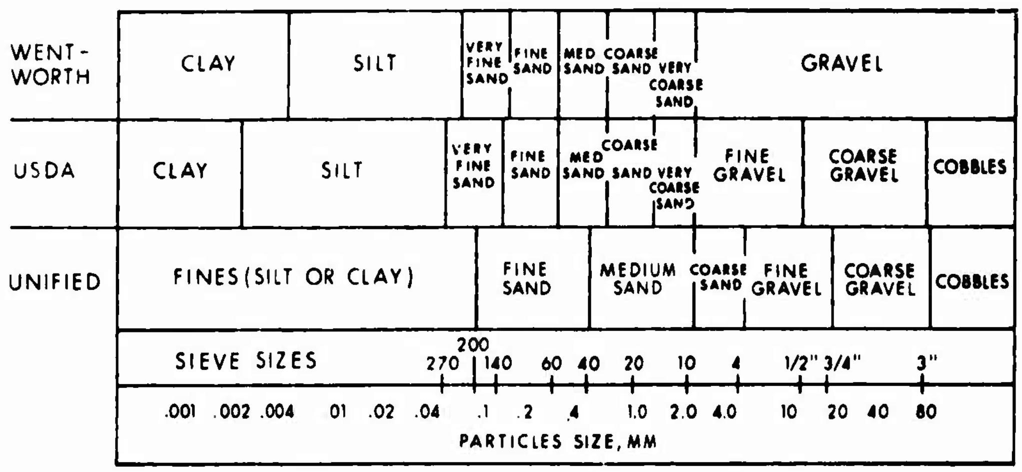
The arrangement of a group of particles in a soil is referred to as its structure. A soil tends to be composed of units resembling a geometric-type figure. In sandy soils, the particles do not adhere. Clay forms into lumps or clods. In some soils, the particles combine into rounded aggregates of varying size. The structure of a soil indicates its capability of cultivation.

(4) Color

Color is the most easily observed and significant soil characteristic. It reflects the physical and chemical processes that formed a soil, it may be an indication of its fertility, and it differs with time, location, moisture content, and temperature. The apparent color may demarcate different major soil groups of the world and the limits of each soil horizon. Dark soils are better absorbers of solar radiation than those of light color and tend to be warmer, depending upon the circulation of air and water in them.

Soil colors range in shades or tints from white to black. The most common are dull shades of red, rust, brown, gray, or yellow. These colors represent variations in degrees of hydration and intensities of the oxides of iron. In humid regions,

COMPARISON OF PARTICLE SIZE OF WENTWORTH, USDA, AND USCS SYSTEMS



WENTWORTH SCALE USED IN GEOLOGIC MEASUREMENT OF SEDIMENTS

SIZE	FRAGMENT	TO GET NEXT LARGER SIZE, MULTIPLY BY	APPROXIMATE EQUIVALENT
	BOULDER		
256mm			10 in
	COBBLE	4	
64 mm			2-1/2 in
	PEBBLE	16	
4 mm			5/32 in
	GRANULE	2	
2 mm			5/64 in
	SAND	32	
1/16mm			.0025 in
	SILT } DUST	16	.06 mm
1/256 mm			.00015 in
	CLAY } DUST		.004 mm

Figure 2. Common Systems of Measuring Particle Size of Soil

a whitish color may indicate a lack of iron, but in arid regions, this color may denote a concentration of alkalinity or soluble salts and a lack of iron. Black and dark-brown colors often denote a high content of organic matter. Reddish brown is high in iron content, but yellow, brown, and mottled colors of them indicate a lack of iron in the soil constituents or poor drainage of the soils.

(5) Water Content

Gravitational, capillary, and hygroscopic water are the three types of moisture in soils. The type and percent of water in a soil have a great influence on the performance and value of a soil as a subgrade material. Excess moisture often reduces the bearing strength and adversely effects other properties of the soil (Strahler, 1963, p. 439).

(6) Soluble Salts

It is important that the presence and type of soluble salts in a soil be determined, because of their possible deleterious effects on construction materials. Also, soluble salts in a soil indicates that its engineering properties may change in the presence of percolating water.

(7) World Soil Types

Contrasts of topographic relief, parent earth material, climate, and vegetation produce a wide variety of soil types that are difficult to accurately classify on a world-wide basis. However, by classifying broad categories of undisturbed soil types as zonal soil groups, well-developed soil profiles can be established for analogous comparison with regions of similar climate, vegetation, and parent material.

3.1.2.2 Engineering Properties of Soils

The combination of internal friction, cohesion, compressibility, elasticity, capillarity, and permeability properties determines the suitability of soils for engineering use. These properties are influenced largely by the soil type and by its gradation, moisture-density relationships, and composition (Terzaghi and Peck, 1948, p.3).

(1) Structural Strength

The load-supporting capacity of a soil varies considerably with its moisture content and density. Methods for determining the strength of soil range from the use of complex formulas and empirical design criteria to controlled field and laboratory tests. Specialized training and experience are required to evaluate a soil for a specific use at a particular location. General estimates of the strength of various soil types can be obtained from published data, but for large structures, field-test data on the entire foundation area are required (Leggett, 1967, p. 1449).

3.1.3 VEGETATION

Vegetation is a prominent feature of terrain and has a great influence on military operations since it affects mobility, concealment, observation, and construction (Carr and Van Lopik, 1962, p. 56; Finch et al, 1957, p. 483).

For terrain analysis purposes, vegetation cover is subdivided into three major categories (Figure 3):

a. Dimension - this includes height, crown shape, stem diameter, and root and stem variations.

b. Physical Properties - the degree of woodiness, deciduousness, leaf characteristics, and spininess.

c. Distribution - the spacing of stems, coverage of canopy, and arrangement of plants.

Vegetation may serve as a source of construction material, fuel, water, or food, It also is an indicator of climatic conditions, soil type, moisture content, drainage, and other surface and subsurface characteristics which are helpful in explaining the differences between terrain.

3.1.4 HYDROLOGY

A body of water is one of the main terrain factors, and its shape, size, distribution, moisture budget, and dynamic properties are factor classes. Other hydrologic information regarding terrain includes flooding susceptibility and controls, tidal variations, local drainage, and climatology (Strahler, 1963, p. 439).

The water supply in an area is dependent upon the sub-surface structure and materials and the amount, seasonal distribution, and type of precipitation in that area.

The total of all the moisture on or near the earth's surface and in the atmosphere does not vary widely from year to year, but exists in a giant circulatory system known as the hydrologic cycle. The cycle originates primarily with the waters of the oceans and seas that cover about three-fourths of the globe.

The occurrence and migration of subsurface water and the semi-permanence of natural water bodies are based (see Figure 4) on the following sequential processes:

a. Evaporation of water from large water bodies.

b. Condensation to produce cloud formations.

c. Precipitation of rain, snow, sleet, or hail upon land surface.

d. Dissipation of the rain or melted solids by direct runoff into lakes and streams, by seepage or infiltration into the soil and underlying rock formations, and by direct evaporation.

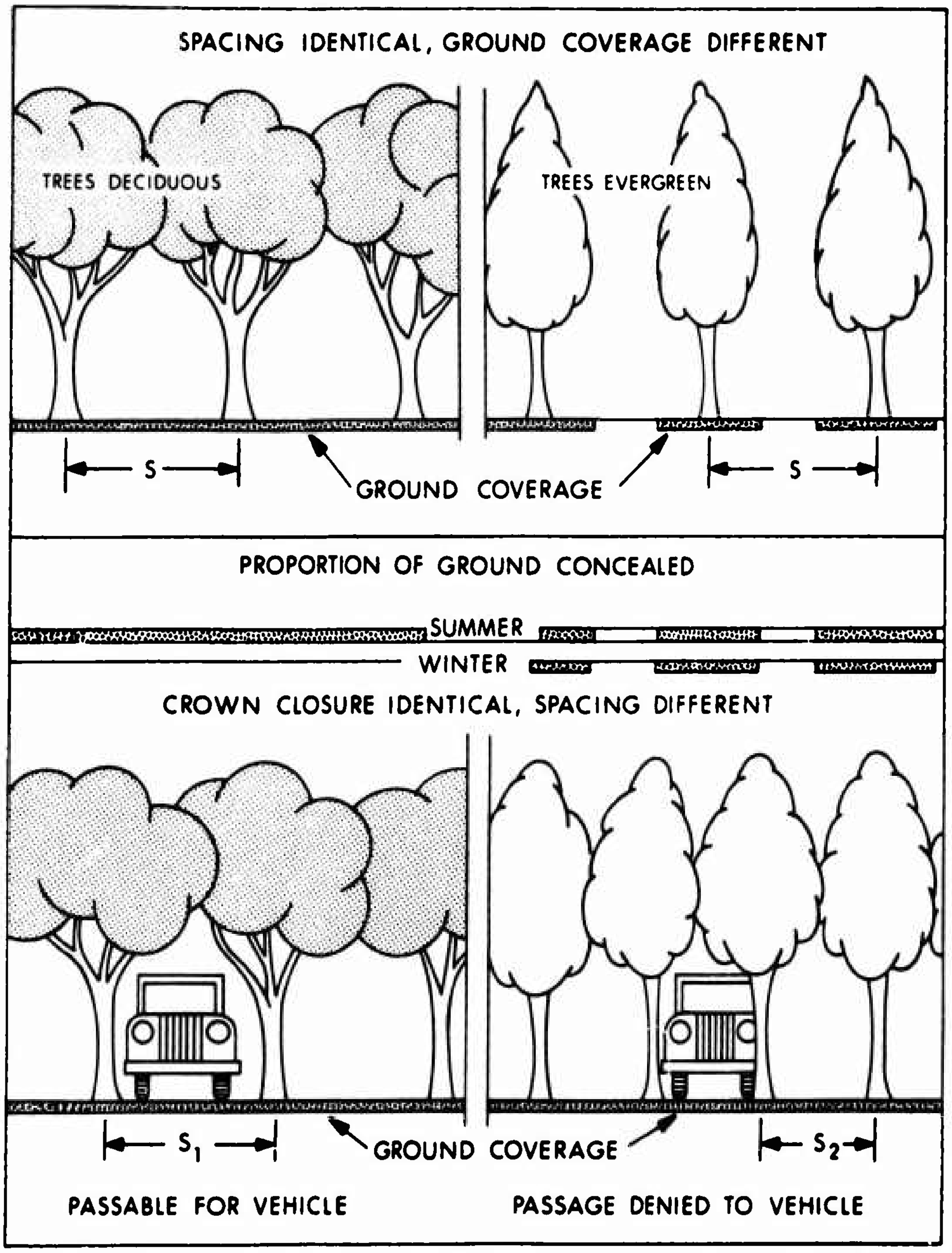


Figure 3. Physical Parameters of Vegetation

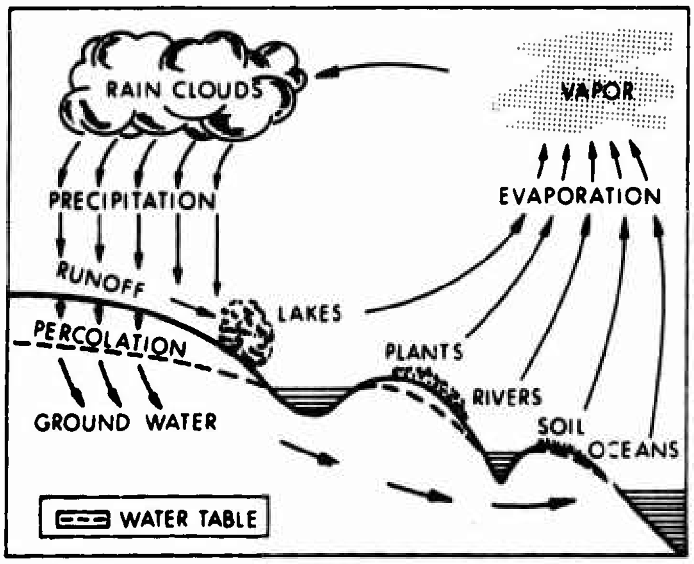


Figure 4. Hydrologic Cycle

e. Movement of water through openings in rocks.

f. Issue of water at the surface through springs, streams, and lakes.

Evaporation from the terrain and transpiration from the vegetation represents the transport of water from the earth back to the atmosphere, the reverse of precipitation. During the period when evapotranspiration exceeds precipitation, the moisture in the terrain profile decreases and results in a drier surface. During periods of excessive precipitation, the moisture index increases, either overcoming a moisture deficiency in the area or creating a surplus. The surplus may result in the formation of new water bodies, glaciers, and snowfields or in the enlargement of the older ones which could lead to flooding conditions (AFM 88-53, p. 90).

The drainage features of various parts of the world display a number of stream patterns. Variations in the pattern are the result of differences in the slope of the land upon which the drainage system developed and differences in the resistance of the underlying rocks to erosion (Figure 5).

The most common drainage pattern, known as dendritic, consists of a tree-like arrangement made up of a main stream and successively smaller tributaries joining it at acute angles; it occurs in regions where the water flows over materials that have relatively similar resistance to erosion. If the stream flows over a regular succession of elongated zones of weak and resistant rocks, such as is formed by folded or faulted structures, a trellis pattern develops. In this pattern, the major streams are arranged in relatively straight parallel lines with tributaries joining at right angles. Single mountain peaks and other places that have

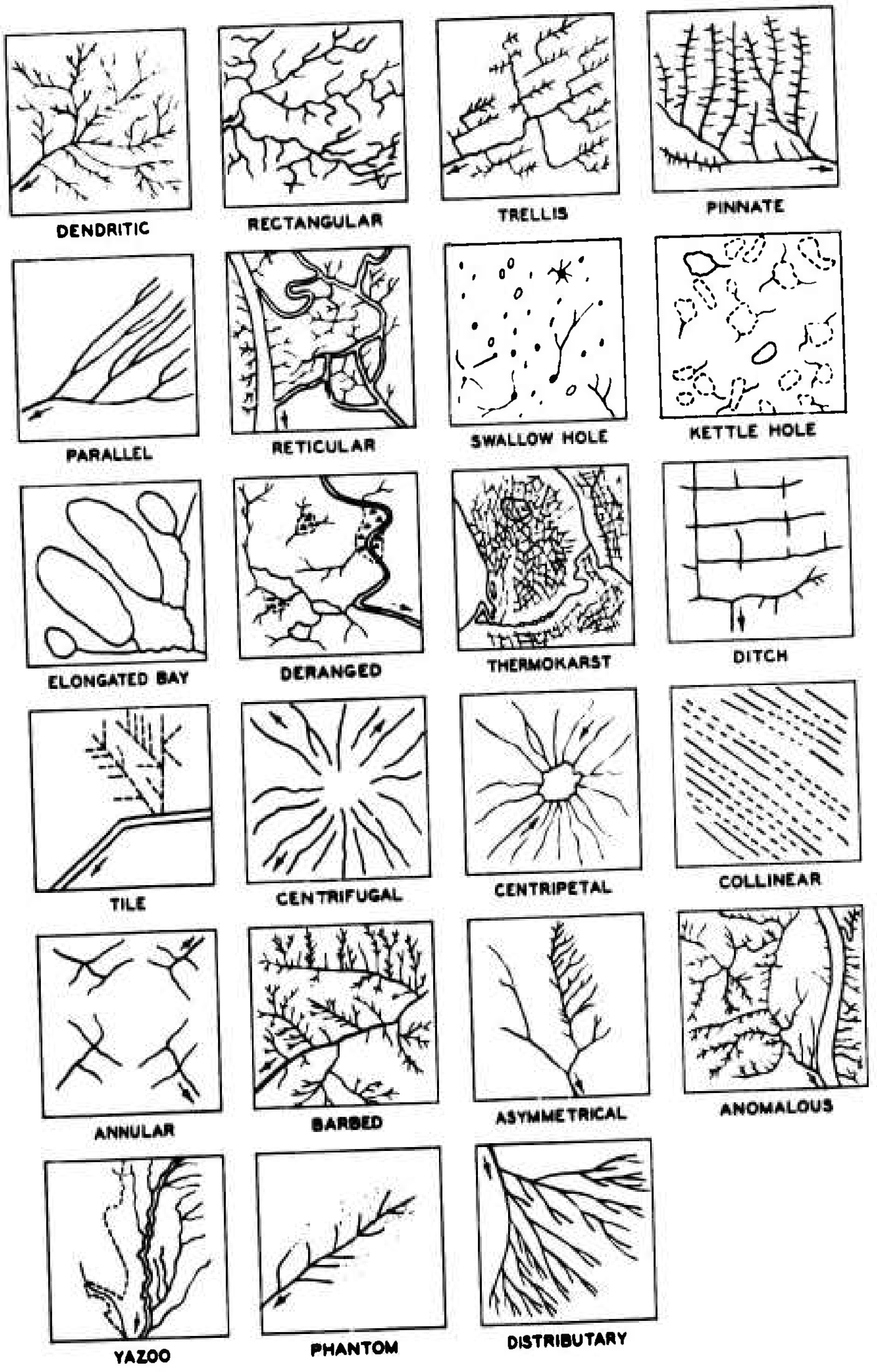


Figure 5. Drainage Pattern Types

a centrally located high area with drainageways extending out from it in all directions have radial patterns. Irregular drainage systems are characteristic of regions that have been covered by continental glaciation.

3.1.5 CLIMATE AND WEATHER

Over a long period, some geographical elements influence the physical and chemical properties of terrain. These elements are: temperature (including radiation), moisture (including humidity, precipitation, and cloudiness), wind (including storms), pressure, evaporation, latitude, altitude, distribution of land and sea, and atmospheric phenomena.

Because these elements vary considerably throughout the world, there are many variations as well as similarities in climate throughout the earth.

Various systems have been formulated to classify climatic types. One noted system, based on the relationship between evaporation and precipitation, was devised in 1931 by C. W. Thornthwaite. He listed five major climatic groups – wet, humid, subhumid, semiarid, and arid – and assigned a rating for "precipitation effectiveness" to each group (Strahler, 1963, p. 327; Air Weather Service Manual 105-3; Curtis, 1966, p. 227).

In 1918, Wladimir Köppen developed a system of classifying the world's climate into 12 primary types according to annual monthly means of temperature and precipitation. His method, frequently modified, is generally accepted by terrain analysts as a suitable systematic and quantitative approach.

3.1.5.1 Major Types of Climate

The Köppen system divided the land areas of the world into 24 groups and utilizes the following 12 classifications to describe the world's climatic types. Figure 6 indicates the geographic locations of these climatic types.

(1) Tropical Rainy Climates (Af, Am)

Rainy tropical climates are characterized by high temperatures and heavy precipitation in all months of the year with no seasonal variation. Other terms used to describe this type are rainy tropics, humid tropical, tropical moist, and tropical rainforest.

(2) Tropical Wet and Dry Climate (Aw)

The type of climate that borders the rainy tropics on their poleward sides has high temperatures through the year and a rainy season followed by one that is distinctly dry. It is also designated by its principal vegetation type as tropical grassland or savanna.

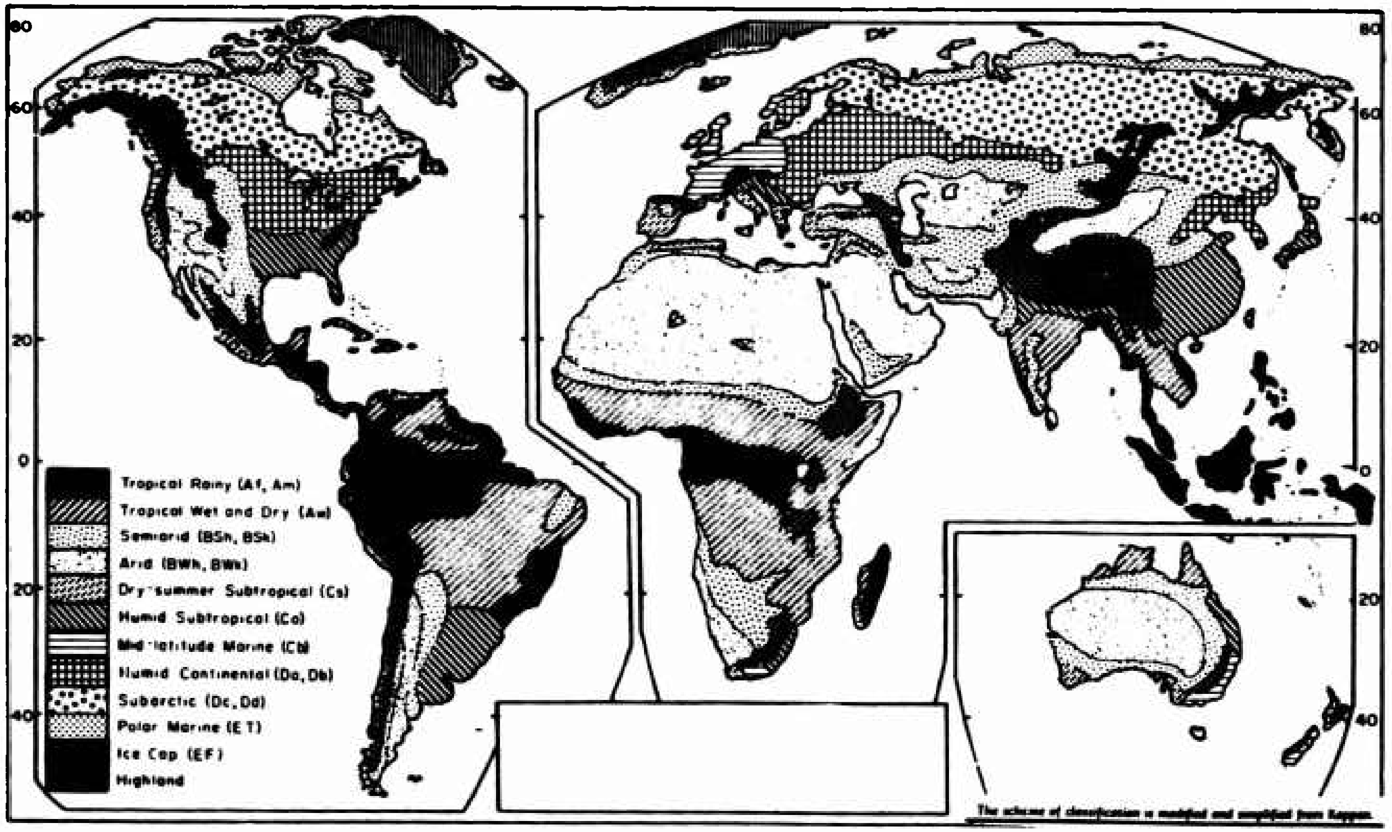


Figure 6. Climates of the Earth (Köppen System)

(3) Semiarid Climates (BSh, BSk)

Broad transitional zones with semiarid climates separate the deserts from the humid climates. Since their one prominent feature is short grass vegetation, these areas are often termed "steppe" climates.

(4) Arid Climates (BWh, BWk)

Arid climates, including deserts, are those greatly lacking in moisture. Many of the arid climates (tropical, subtropical, and mid-latitude arid) have an annual precipitation less than evaporation.

(5) Dry Summer Subtropical Climates (Cs)

This type is characterized by a high percentage of sunshine in all seasons, and by dry, warm to hot summers and mild, rainy winters. Since such conditions are most widespread in the borderlands of the Mediterranean Sea, the climatic type is often termed as Mediterranean or Mediterranean subtropical.

(6) Humid Subtropical Climates (Ca)

Areas with this climatic type are on the eastern sides of continents in the lower middle latitudes and have hot summers, mild winters, and abundant precipitation in the warm season.

(7) Mid-latitude Marine Climates (Cb)

In many coastal regions of the middle latitudes, particularly west coasts, the climate is characterized by mild winters, cool summers, and relatively high precipitation. This type of climate is also designated west coast marine or temperate marine.

(8a) Humid Continental Climates, Warm Summer Phase (Da)

This climate has great differences between the long hot summer and cold winter temperatures, changeable weather in all seasons, and some precipitation.

(8b) Humid Continental Climates, Cool Summer Phase (Db)

The cool summer phase of this climate is similar to the warm summer phase as described in (8). The major differences are that the cool summer is shorter as the result of lower temperatures in the high latitudinal locations.

(9) Subarctic Climates (Dc, Dd)

This climatic type has long cold winters, short summer seasons, and great extremes of temperature. Other terms used to describe it are polar continental, boreal forest, or northern coniferous forest.

(10) Polar Marine Climates (ET)

The Arctic and Antarctic regions have a harsh environment with very low temperatures.

(11) Ice Cap (EF)

The two types of polar climates are polar marine and ice cap. They have similar harsh environments and weather characteristics, but vary often within and between the arctic and antarctic regions. The ice cap climate has severe cold temperatures, high winds, light precipitation, and a short summer-like season with a few days above freezing and sunshine.

(12) Highland

Differences in elevation and in exposure to winds and sunlight result in a great variety of climatic features in highland regions. Mountain climates cannot be easily classified on the basis of similar temperatures and pressures on a world scale. Climates of mountainous regions are frequently termed undifferentiated highland.

3.2 Methods of Analysis

3.2.1 DATA ACQUISITION METHODS

Three methods are used for acquiring terrain data: contact, non-contact, and indirect. These methods are described briefly below and fully in Appendix C (see Figure 7).

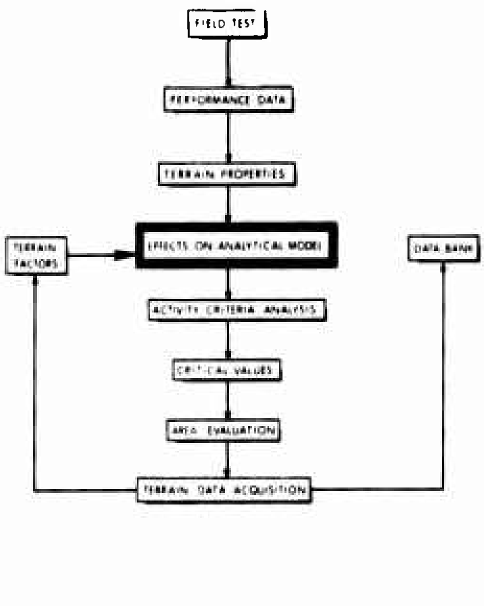


Figure 7. Data Acquisition Cycle

In the contact method, direct measurements of factor and factor class values are made on the ground. This method is the most reliable, since it yields usable quantitative data, but it is costly, time-consuming, and not always feasible.

In the non-contact method, remote-sensing instrumentation is used to obtain images of the terrain or recorded values of emissions from certain terraim properties (Figure 8). Although the non-contact method is easy to use and expedient, the accuracy and reliability of the resultant data are much less, generally, than are those of the contact method. The non-contact method is described in detail in Chapter III.

The indirect method of terrain data acquisition is employed when measured data are lacking and an area is inaccessible. Basically, the method entails employing intuitive scientific deduction to obtain an appropriate analogous analysis. Certain terrain characteristics can be predicted by comparing an unknown area to a known area that is similar in geology, topography, landforms, soils, climate, and vegetation. This method is frequently used in combination with the others to provide supplementary information to an analysis (Grabau, 1967b, p.18; Belcher, 1948).

3.2.1.1 Terrain Evaluation

The rationale of evaluation is largely the development of reasonable conclusions from an analysis and interpretation of measured and inferred data. The conclusions must relate the influence of terrain on a proposed activity whose performance can be predicted in any defined terrain complex (Figure 9).

Terrain studies for military application have the following specific goals:

a. Terrain Classification, Quantitative (describe, classify, map, and establish analogs)

b. Effects on Military Activities in Known Areas (available data and specialized experience)

c. Factor/Effect Relationships (theoretical analysis)

d. Field Testing of Theoretical Studies (validation of critical values)

e. Sensors for Determination of Terrain Factor Values (remote sensing from airborne or orbital altitudes)

f. Prediction of Quantitative Effects in Unknown Areas (elimination of pre-mission reconnaissance)

g. Data Storage and Retrieval (accumulation of information for prediction)

h. Selection of Flexible Alternative Conditions (varied response to meet changing tactical situations and environmental factors)

(1) Performance Prediction

The most efficient prediction concerning the success (that is, performance) of a proposed activity is achieved when all the requirements of a proposed activity and all terrain factor values are known prior to the evaluation. The principles

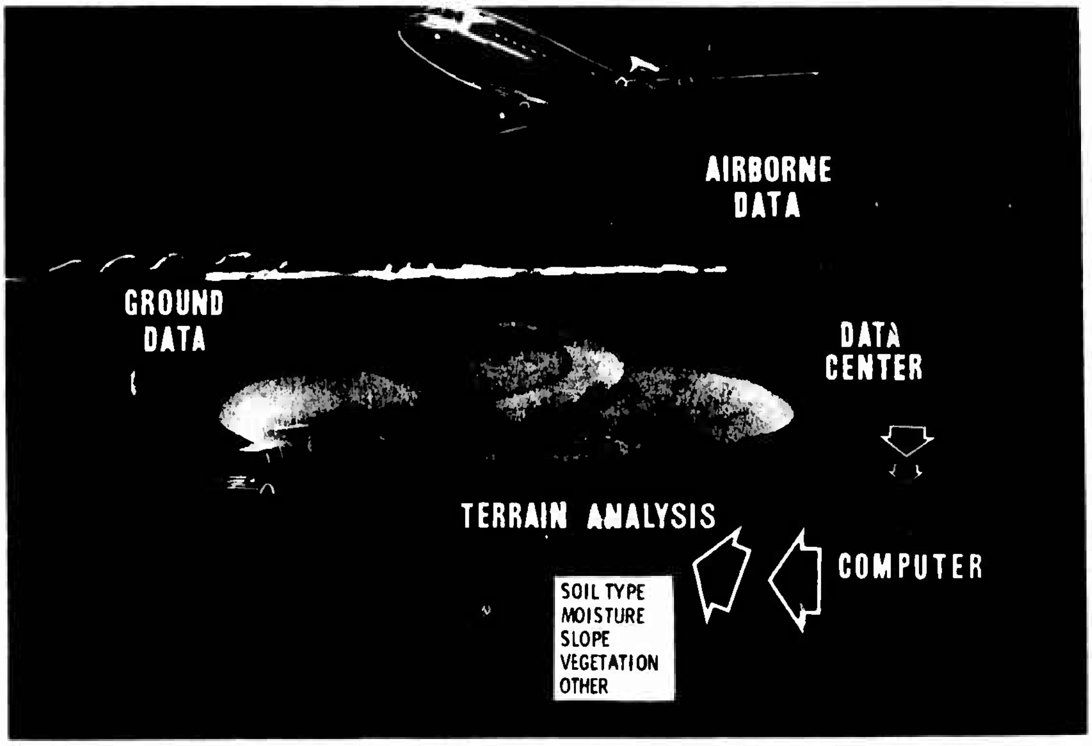


Figure 8. Synthesis of Data From Non-Contact and Contact Methods

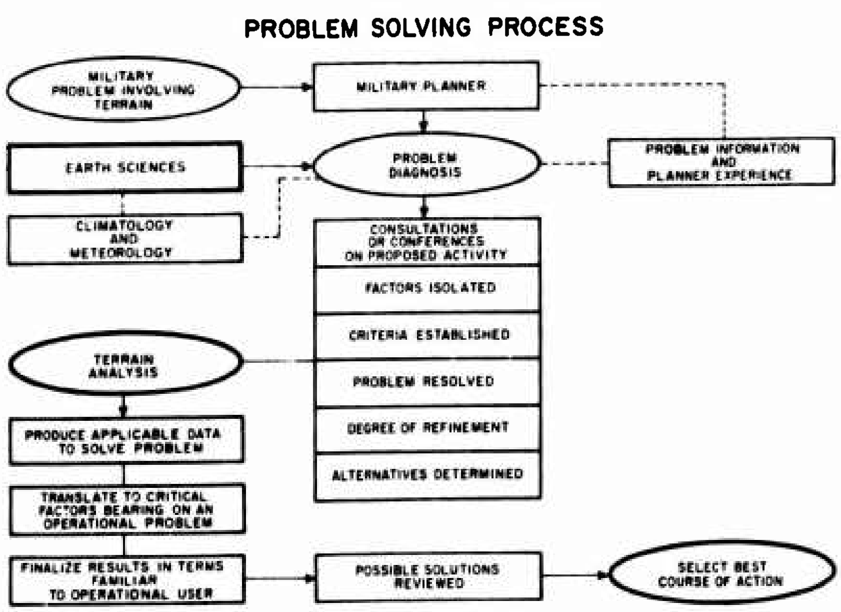


Figure 9. Terrain Evaluation for Military Use

governing an objective, rapid, and accurate evaluation of terrain are: (a) the relationship between the terrain and the activity must be known in mathematical terms in the study and analysis phases; (b) a set of analytical models for each selected terrain factor relevant to the activity must be formulated; and (c) the evaluation must be based on the designated factors in the models and their critical values (Grabau, 1967b, p. 18).

(2) Evaluation and Prediction Procedure

The procedure for obtaining and disseminating evaluation and performance-prediction data is outlined below and shown diagrammatically in Figure 9. The terrain analyst should:

a. Define and understand the military need and delineate specific activities in mathematical terms.

b. Isolate the relevant terrain factors and their subclasses and construct a mathematical model of each subclass.

c. Determine the critical terrain factor class value for each model.

d. Obtain and analyze all relevant terrain factor data near the site of the proposed activity.

e. Determine the gaps in the required data, and plan to obtain that data.

f. Analyze all the information and make preliminary conclusions.

g. Consult with knowledgeable professionals and/or technicians on any hazy aspect of the total problem.

h. Review the analysis of source information, evaluate for specific effects on the activity, and make final conclusions and recommendations. Consider vulnerability of terrain to possible enemy action.

i. Prepare a report covering all major aspects of the problem, and include in it large and medium scale maps, annotated ground and aerial vertical and stereoscopic photos, charts, diagrams, graphs, engineering data, and important references. Radar, infrared, other film (color, camouflage detection), and other imagery would be included.

j. In cases of major problems, document all important information in detail. The conclusions and recommendations should be brief, clear, complete, and supported by data or information contained in the body of the report. Useful photographic documentation, and other imagery properly annotated, should be included as appendix material.

k. The team concept of analyzing a problem or activity should be the standard procedure. A special group of three to six professionals or technicians should be assigned the problem, with a target date for completion. The professionals should be from such fields as civil engineering, geology, geography, soil science, botany, ecology, forestry, and photogrammetry.

1. The terrain analyst will emphasize the foregoing steps related to his particular objectives, using the basic concepts of his scientific field, the criteria which they provide, and applying the method of reasoning appropriate to the problem. In the absence of specific data, the interpretation is based on reasoning by analogy. For this step, comparison of the unknown terrain complex with its nearest analogous terrain of known characteristics is the primary point of departure in the analysis.

The possibilities suggested by such comparisons are subjected to independent checks before any final judgment is rendered. Critical examination is made to appraise the correctness of the analogy, to consider possible ambiguities, to explore alternate explanations, and to ascertain the extent to which explanations conform with basic principles and data of the scientific disciplines. Analysis and synthesis of the data compared with the analogous conditions can contribute to a reliable evaluation.

(3) Special Procedures for Site Selection

As a supplemental guidance to the approach outlined in (2), the following steps will provide the required data for effective integration, reduction, and evaluation in response to the varying siting problems.

a. Determine data on: regional and local topography, geology, hydrology, soils, vegetation, climate and weather, and accessibility (roads, railroads, air, water, and ports).

Terrain data of engineering significance includes:

1) Regional relief within a 25-mile radius of the potential site with about 20-ft accuracy, local relief within a 5-mile radius with about a 10-ft accuracy, and site area within a 3-mile radius with about 1-ft accuracy
2) Soil profile down to 10 ft or bedrock
3) Surface and ground water characteristics
4) Geological conditions
5) Vegetation location and type, root systems, and density
6) Meteorological factors
7) Accessibility and logistics requirements
8) Perimeter defense advantages.

b. Prepare and compile all the data in item a., above, in large, intermediate, and small scale maps appropriate to the type of use and annotate the aerial and ground photography details.

c. Conduct a survey of the site to determine availability of local indigenous construction materials, water supplies (potable and construction), and topographic controls.

d. Prepare engineering plan of site layout and development.

e. Compute grading and excavation requirements, estimate effort required to remove obstacles, and plan for protection against serious natural hazards.

f. Perform final evaluation of all the environmental factors influencing the site utilization.

g. Compute the total construction effort and resources in terms of personnel, equipment, materials, and time needed to ready the site for use.

h. Prepare final report in a folio form on the site including recommendations, alternate sites, advice in site preparation, accompanied by properly annotated overlap maps, ground and aerial photographs, and other essential background information.

i. Check with user to record for future guidance the comparison of predicted site conditions and recommended effort with the final site selection, development, and expended construction effort.

Selection of sites for installations, tactical positions or mobility of weapons and troops, and aircraft and vehicle trafficability generally follow a similar plan of investigation.

3.2.2 CAPABILITIES AND LIMITATIONS OF TERRAIN ANALYSIS

Experience has demonstrated that significant savings of time and effort in terrain interpretation are obtained by a combination of contact and remote-sensing methods. The viewing of terrain in three-dimension, thus presenting it in realistic perspective, is invaluable for improved planning. The non-contact and indirect methods have limitations which degrade an optimum analysis of terrain in completely quantitative terms.

3.2.2.1 Masked Terrain Conditions

One of the major limitations to an accurate evaluation of terrain is that surface materials can mask the diagnostic characteristics of underlying formations. Vegetation, glacial remnants, and wind-blown or water-transported materials are common types of masking deposits. In addition, relic and pseudomorphic landforms produced from different materials, conditions, and geologic processes are unfamiliar varieties and can confuse the interpreter. Current knowledge regarding the origin, distribution, and relationships of many known types of landforms is inadequate, and additional varieties remain to be discovered and studied. Although external characteristics may be diagnostic of internal conditions and underground materials, the interpreter is handicapped unless the surface details of the terrain are evident and simulate the classic examples of landforms.

3.2.2.2 Available Information

Terrain data obtained for other objectives (economic or agricultural purposes, etc.) is available, but it is generally not directly applicable to specific military needs. Photointerpretation used in conjunction with this data could provide some of the necessary details.

3.2.2.3 Quality and Accuracy of Source Materials

The reliability of interpretation is proportional to the availability of large-scale, recent, and accurate maps and photographs (aerial and ground). Ideally, the map and photo scales for microterrain studies should be from 1:2,000 to 1:10,000; for general terrain analysis they should be from 1:15,000 to 1:40,000. Many interpretation difficulties arise from the need to use expedient procedures and maps and photos of unsuitable scale and poor quality. Factors of cost, time, priority, or specific requirements often outweigh the interpreter's preference and limit the reliability of his interpretations.

3.2.2.4 Training and Field Experience of the Interpreter

The level of skill, formal training, and field experience of an interpreter directly affects the quality of his analysis. Many of the subtle phases of interpretation - denoting interpretative skill and confidence - are not developed until a number of successful predictions have been achieved in unknown areas. The common weakness is lack of training in a pertinent scientific discipline.

3.2.2.5 Inadequate Methodology

To overcome existing limitations in the field of terrain analysis, a source of ready and reliable data must be made available to the interpreter. This goal could be achieved by the establishment of a data bank, by continued effort to supply and store new data, and by incorporation of the following types of information:

(1) A Global Atlas of Regional Landforms - Aerial Views

Representative examples of landform types and their variations in all types of geologic, geographic, and climatic environments should be depicted in an atlas. Comparisons of different geographic areas with analogies in accessible areas such as in the United States would be included.

(2) Types of Terrain Features

The characteristics of the terrain from microfeatures to vegetation, soil conditions, bedrock, surface and subsurface drainage, and other related factors such as engineering properties within the global environment should be summarized and illustrated in detail. Such summaries would compare stereographic data of familiar areas with that from unknown areas.

(3) Case Histories of Terrain Studies

Detailed reports on locations that were checked on the ground and the results compared with data obtained through remote sensing would be of great value as background, training, and reference material. Such reports would describe the predictions made, criteria used, source data, and the extent to which predictions were confirmed by ground testing. The reasons for inaccuracies in the interpretation would also be covered. A folio of all site maps, charts, graphs, aerial and ground photographs, and other imagery, plus supporting bibliographic references, would be a part of the documentation.

(4) Increased Use of Illustrations & Annotated Imagery

All reports issued on the investigation of terrain should contain annotated photographic and other imagery showing terrain characteristics. This would contribute to an increase of background information for further reference and analysis.

(5) Further Research

Fundamental research through controlled experiments should be continued on the origin, nature, and distribution of landforms and microfeatures and their properties in different environments. Bare, natural, and cultivated vegetated surfaces should be investigated for clues to specific terrain conditions that can be recognized on aerial imagery (Williams, 1964, p. 98; Neal, 1965, p. 150; Needleman, 1962, p. 70).

As new types and varieties of terrain are studied, variations must be inventoried, scientific complexities must be unravelled, ambiguities resolved, and controlling factors evaluated. This new information could facilitate improved terrain interpretation (Committee on Geophysics and Geography, 1953, p. 26).

4. CRITERIA

Since the critical values of terrain parameters change with each new military application (size of tanks, etc.), a thorough knowledge of the geology of the ground feature and the surrounding terrain is necessary in order to determine the engineering properties. The critical values are based on the quantitative effect that the application will have on the individual natural features.

The criteria established from performance tests, etc., determine such applications as trafficability of aircraft, vehicles, and troops; concealment and cover; availability of water and construction materials; and types of construction problems.

5. VALIDATION

The quality of the terrain evaluation is directly proportional to the useability of the investigated terrain according to performance predictions. Reliability is increased if the predictions are supplemented with adequate measured data. The best approach is to use the data in a check and balance method to eliminate possible limitations in the proposed use of the terrain for each application. Field, laboratory, and sub-surface investigations can either confirm or deny such use. Comparison of unfamiliar terrains with their nearest analogues of known characteristics and performance predictability is the standard practice in lieu of sufficient ground data (Burns, 1960, p. 25; Needleman and Pressman, 1962, p. 190).

III. Remote Sensing

C. E. Molineux

1. INTRODUCTION

In terrain analysis, aerial photography is the most widely used type of remote sensing, and most of the photos obtained are black-and-white, taken on panchromatic film at scales ranging from 1:10,000 to 1:50,000. Such photos, used in conjunction with on-the-ground observations, usually provide the best means of obtaining a ground inventory. To be of maximum usefulness, the aerial photography must have been taken with proper consideration given to film, filter, resolution, time of day, and season of the year. Each land structural element has a critical scale that is optimum for interpretation, and the photo patterns pertaining to the distribution of tones and textures of an image are critically important.

Electromagnetic sensing outside the visible spectrum is not extensively used at this time, but research and development are in process, especially in the imaging infrared and radar regions. As experience is accumulated, such imaging or non-imaging sensors will come into greater use and acceptance.

Non-imaging sensors usually record a phase of electromagnetic radiation emitted or reflected from a surface. The phase may be an absolute quantity in various spectral regions, such as radiometric temperature, or time-distance relations of received radiation, as in microwave or radio-frequency-reflection devices. The relationship may be phase or polarization, absolute reflectivity

values, or similar factors associated with sub-surface conditions determined by the radio-frequency penetration capability of such devices. Gamma-ray sensing, radio-frequency sounding, and swept-frequency radar techniques are examples of this capability.

Some limitations are due to the relationships of the terrain electromagnetic emissivity and the sensor's capability to detect or record the same.

In general it may be said that aerial photography enables estimation and limited measurement of the physical and engineering properties of surficial terrain. Infrared sensing in the 3 to 5μ wavelength region of the spectrum best indicates cultural or artificial thermal energy sources. Infrared in the 8 to 14μ region coincides with the broad envelope of natural earth radiation, and enables sensing of surface or near-sub-surface soil conditions that are important for mobility purposes.

Microwave radiometry has much promise for terrain material identification and discrimination and for mapping of sub-surface conditions. Radar techniques have great potential for distinguishing surface materials, determining moisture content and vegetation conditions, and for recording engineering geologic patterns such as outcrops, faults, and stratification. Airborne magnetometry is useful in mapping near-surface igneous material.

To expedite the acquisition of reconnaissance, engineering, and geologic data, remote sensing methods are used. Basically, the method entails acquiring information about an object or phenomena by using an information-gathering device that does not have to come in contact with the object under investigation. The data obtained by remote-sensing devices can be utilized to further our knowledge relevant to the earth and its environment, to solve engineering problems and problems relevant to the exploitation or conservation of natural resources, and to promote national defense. The USAF Scientific Advisory Board (AFSAB) has recently endorsed the need for continuing such application of remote sensing techniques (USAF Scientific Advisory Board, 1966).

Present electromagnetic sensing technology and the ability to operate from platforms above the earth has permitted the development of systems having a greatly increased ability to sense the meaningful characteristics of the earth and its environment. Increased information can be obtained through the use of combinations of sensors, with each individual sensor exploiting a different portion of the electromagnetic spectrum. Infrared, radar, passive microwave, geochemical, spectrophotographic, and spectroradiometric sensor techniques show much promise in providing surface and subsurface information. Much of this information is also needed in target-background, signature-characterization efforts.

With remote sensing devices it is possible to map large areas, obtain information about the physical characteristics of objects or phenomena, and monitor conditions that change with time. Regardless of the application, especially when used in aircraft or spacecraft vehicles, these devices provide a means of acquiring data on environments otherwise inaccessible because of physical limitations or political restraint. In some instances, remote sensors may be the only means of acquiring a certain type of data; in others, they may be the more economical means. The vast potential of satellite sensing has been documented for NASA by the University of Michigan (University of Michigan, 1966a). In addition, non-imaging sensors (including air-droppable devices) can be used to obtain specialized data. Ground-based surveys, when feasible or allowed, may use additional sensors that require contact with the surface to obtain unique data. In the airborne mode, information obtained photographically in the visible portion of the spectrum can be supplemented by data recorded by other sensors used in a multi-disciplinary approach.

Various charts and effectiveness diagrams tabulating the terrain and environment parameters detectable and measurable by pertinent remote sensing techniques have been prepared by organizations conducting such activities. One such comprehensive chart prepared by the U. S. Army Engineer Waterways Experiment Station (USAEWES) is shown as Figure 10. Others are plentiful in the literature. The electromagnetic spectrum, sub-divided to show the generally accepted sensing regions, is drawn in terms of frequency and wavelength in Figure 11.

Countless governmental, industrial, and university organizations are conducting research and development, testing, and determining the applications of remote sensors. Indicative of the general interest and emphasis in this scientific field is a long-term comprehensive study by the University of Michigan, supported by many federal agencies, which has featured periodic Symposia to provide an information exchange medium on the state-of-the-art and applications of all unclassified phases of remote sensing (University of Michigan, 1962, 1963, 1965, 1966b). NASA has published extensively on the use of remote sensing in its earth resource program (Badgley et al, 1967), and an International Symposium on Electromagnetic Sensing of the Earth from Satellites was held in late 1965, sponsored by American Geophysical Union, American Meteorological Society, and the Optical Society of America (Zirkind, 1967). The Michigan Symposium proceedings and the Journal "Photogrammetric Engineering" of the American Society of Photogrammetry (ASP) are highly recommended for presentations of current status and applications.

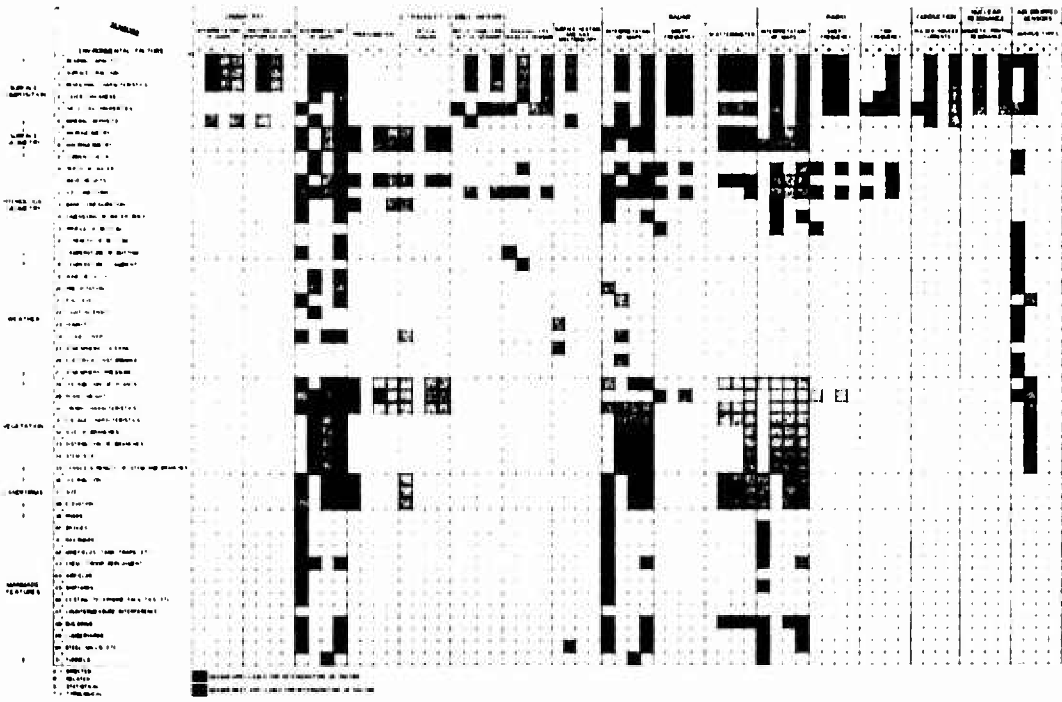


Figure 10. Remote Methods for Characterizing Environmental Factors

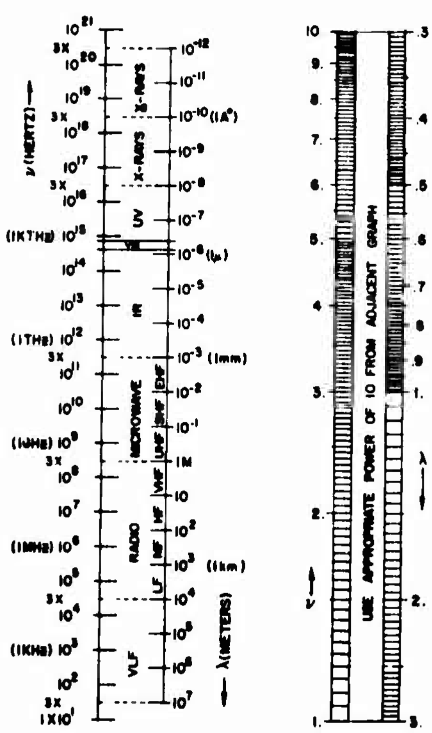


Figure 11. The Electromagnetic Spectrum and Frequency Wavelength Conversion Nomogram

2. AERIAL PHOTOGRAPHY

The principles and uses of aerial photography using conventional black-and-white film are well known and will not be re-stated here. Such photography with panchromatic film uses the complete visible spectrum, except that haze, or minus-blue, filters are occasionally introduced. It provides a high resolution and generally distortion-free visual map of the terrain essentially as the human eye perceives it. In this type of photography most images have the objects of interest recorded in varying shades of gray on the photographic emulsion. The problem of photo-interpretation begins here. In many situations the image is of a familiar object or terrain feature, and its geometric properties (size, shape, shadow, or texture) plus its location, contrast, and relationship to surrounding objects enable ready identification. However, when the object is unfamiliar or exhibits a different or unaccustomed tonal value on the image, the interpreter's judgment and experience becomes critical (American Society of Photogrammetry, 1960, p. 99).

2.1 Resolving Power

For a given film format (W), the smallest detectable elevation feature is dependent on the flight altitude (H) and the resolving power of the camera system (R). This is expressed as $\frac{\Delta H}{H} = \frac{1}{274WR}$ where ΔH, H, and W are in feet and R is the commonly used term of lines per millimeter. This capability is shown for various $\frac{\Delta H}{H}$ combinations using a 9-inch film format in Figure 12. The range of resolution hachured (up to 80 lines per millimeter) represents that presently in the unclassified state-of-the-art of aerial photography (Itek, 1962, p. 50).

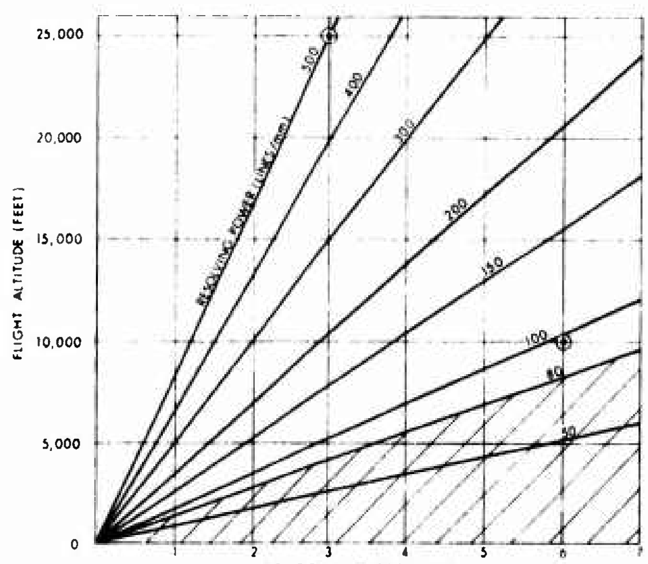


Figure 12. Resolving Power of Photography Varying With Flight Altitude

2.1.1 GROUND RESOLUTION

Photographic interpretation for detail from aerial photography ranges from scales of 1:2,000 to 1:10,000, with ground resolution of object size obtained in terms of inches. In contrast, the common scales for photointerpretation for reconnaissance purposes range from 1:10,000 to 1:40,000, with ground resolution attainable in terms of feet. The common photographic mapping scale is 1:60,000, depending on the use of adequate ground-control points (American Society of Photogrammetry, 1960, p. 773).

The use of aerial color photography greatly extends the criteria that can be used for terrain property identification. Although the human eye-brain combination can only discriminate about 128 shades of gray, it can discriminate several million different colors.

There are many problems associated with the use of aerial color photography, apart from the cost of this film and the necessary processing techniques. The glass covering the camera wells in photographic reconnaissance aircraft are rarely of high optical quality and may act as an image-degrading filter with color tones appearing on the emulsion being different from the natural object colors. The optical properties and color correction of the camera lenses themselves, the quality, amount, and atmospheric absorption of the reflected solar radiation, and the variability of the dyes making up the film e[illegible]ion itself are other factors that can contribute to image color variability. The American Society of Photogrammetry has published a "Manual of Color Aerial Photography" that is highly recommended for pertinent information. A voluminous report entitled "Photographic Instrumentation - Science and Engineering" prepared for the Naval Air Systems Command (Hyzer, 1965) gives a thorough coverage of all photographic equipment and applications. The Navy Oceanographic Office (Vary, 1967) has recently conducted a test of the water-penetrating ability of color photography, in flights from 2000 to 30,000 ft altitude. It was found that 100-ft-sq offshore targets could successfully be detected at depths of 65 ft, even in rough water at sun angles from 20° to 40°.

Color photography from satellite altitudes provides coverage of earth areas of unprecedented scope and contrast. An example of this capability is the preparation of tectonic maps of the Middle East at one to one million scale by the North American Aviation Science Center under NASA support (Abdel - Gawad, 1967). These maps, prepared entirely from GEMINI photographs, show faults, shear zones, and geologic structures, often extending for hundreds of miles, that are unrecognizable in lower-scale photography.

Aerial panoramic cameras have been developed and used for over a decade to combine wide-area photographic coverage with very high resolution. They generally have a curved film plane and a high-quality, narrow-angle lens that scans across the flight path of the aircraft so as to "paint" an image of a wide

swath of ground onto the film. The maximum scan angle is 60° either side of the vertical. With a focal length of 12 in., very high altitude photography can be obtained without sacrificing image detail. Since the center of the lens rotates with the scanning arm, the sharpest possible image is always recorded on the film, even at the edges of the format. An example of the scope and high resolution of panoramic aerial photography is shown in Figure 13.

Modifications to aerial color film to eliminate the blue-sensitive layer have recently been proposed to film manufacturers. The standard yellow haze filter would, therefore, not be needed, and a one-stop increase in exposure would be possible.

2.2 Multispectral Photography

Multispectral, multiband, and spectro-zonal photography are terms applied to the images simultaneously obtained through various filter combinations in narrow-band regions of the visible and near-infrared spectrum. The operating

Figure 13. Aerial Panoramic View of Terrain

principle of this technique is that different types or conditions of terrain reflect solar radiation differently throughout the photographic spectrum. By interpretation of the relative brightness or tonal contrast appearing on matched, narrow-band images, changes in soil or vegetation properties and composition or seasonal effects on the terrain can be detected and analyzed. Such information can be obtained in a more quantitative manner from this type of aerial photography than from conventional black-and-white or even color photography.

A nine-lens camera system (Figure 14), originally developed for ARPA nuclear test detection program (Molineux, 1965), has been used extensively by AFCRL and NASA for airborne terrain research programs. This "multiband" camera employs three rolls of film, each traversing three matched lenses equipped with appropriate filters to give a narrow-band input to the film. The part of the spectrum covered is from 400 to 900 mμ, with resolution of approximately 75 lines per millimeter. The resulting nine photographs, taken at one shutter click, are matched within 0.001 in. Six of the images are on two rolls of 70 mm aerial panchromatic film, and the other three are on one roll of 70 mm aerial infrared film. The lenses used are f/2.4, 150 mm with standard gelatin filters that give bandwidths of about 100 Mμ.

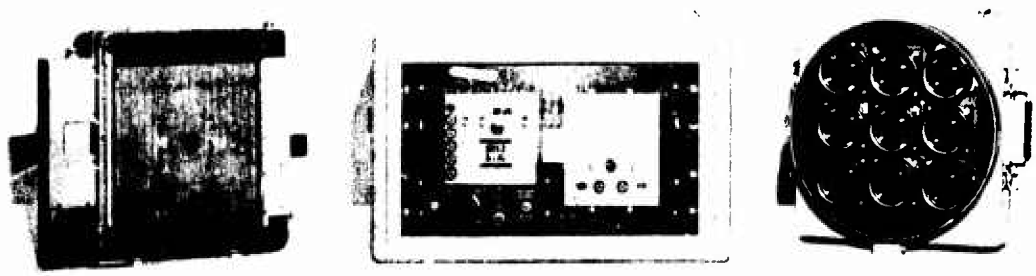


Figure 14. Multiband Camera System

Extension of the camera's capability to gather signatures of terrain properties is provided by the use of horizontally and vertically polarized filters in two of the bands, and an ultraviolet transmitting lens in another band, applied when desired. The camera has image motion compensation, and can be flown at altitudes of from 600 ft to over 25,000 ft. A stabilized mount is desirable to provide vertical control of photographic coverage. A wide range of shutter speeds and apertures are available for use over varying conditions of terrain illumination.

AFCRL's use of the multispectral camera has covered terrain areas ranging from arctic glaciers through lava flows and coastal beaches to desert playas and tropical rain forests, all of interest because of their characteristic reflectance

properties. Analysis involves examination of the nine images from each exposure on a light table modified to display the three rolls of film together. Terrain anomalies or patterns of interest can be identified in terms of their reflectance changes for correlation with known patterns and conditions; selected frames can be used for color enhancement or superposition techniques, if desired. In special cases where very subtle tonal differences are worthy of more analysis, a microdensitometer can be used to scan the original negative and yield the detailed reflectance values that were registered as gray tones.

The nine bands were originally chosen to provide wide coverage throughout the spectrum. Since some of these may give no additional or otherwise redundant reflectance information, a lesser number of bands may be practical. Other government agencies (Rome Air Development Center, Army Terrestrial Science Center, and National Aeronautics and Space Administration) and many commercial aerial photographic organizations have developed four-band cameras by clustering four separate 70-mm cameras and synchronizing their shutters, which enable worthwhile multispectral photography.

An example of the imagery generated by the nine-lens systems of AFCRL, and the interpretation of the tonal changes evident in contrasting wavelength regions, is shown in Figure 15.

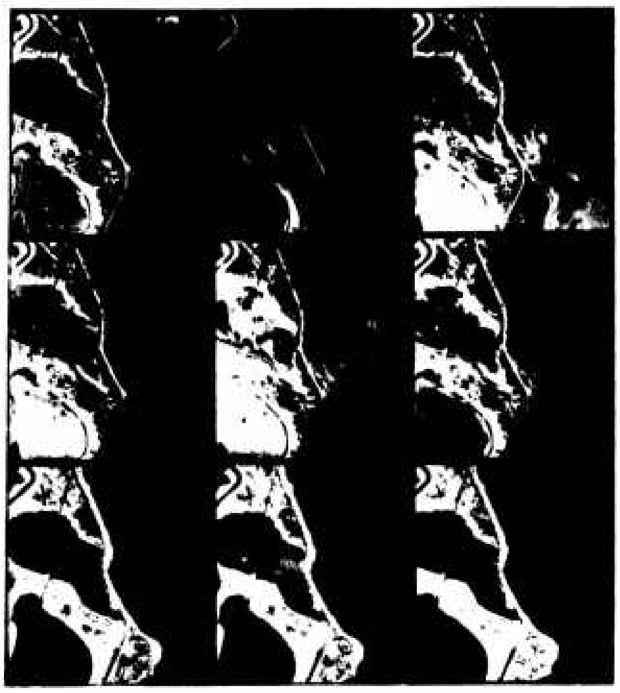


Figure 15. Multiband Photography

2.3 Color-Distortion Photography

"Camouflage Detection" (CD) or Ektachrome Infrared (IR) film is a high-resolution, false-color film that differs from normal color film by having its three sensitized emulsion layers record green, red, and infrared radiation instead of the usual blue, green, and red. It has high color contrast, brilliance, and haze penetration capability. The colors, although appearing false to one's experience, provide a contrast enabling adjacent objects or materials to stand out distinctly. Although the high-resolution values cited by the manufacturer are not generally realized through exposure and processing, the clarity of CD images provides greater detail than comparable color or IR images. Figure 16 illustrates the visible spectral and sensitivity ranges of pertinent films.

The use of color-distortion photography also enables distinction between types and health of vegetation cover. Deciduous green foliage reflects green and infrared radiation, and film processing leaves magenta as the indicator for such vegetation; coniferous foliage is recorded as a darker magenta. Due to changes in IR reflectivity of foliage pigments, dead or diseased leaves are recorded in shades of light magenta to orange. The effectiveness of using CD film for determining vegetation cover properties has been pioneered and established by Dr. Robert Colwell at the University of California (Colwell, 1966).

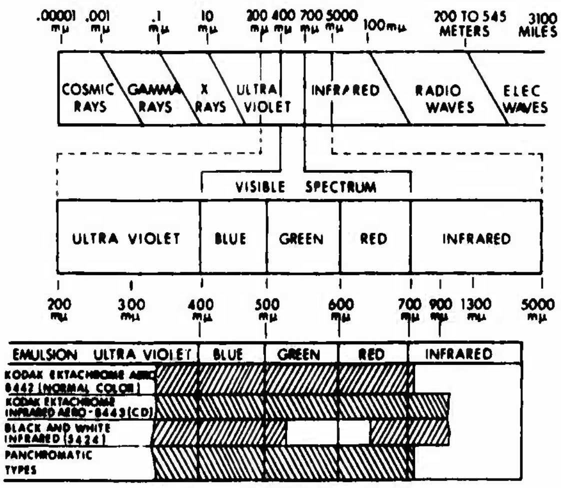


Figure 16. Electromagnetic Spectral Sensitivity Ranges of Films

In addition, the use of color emulsions, particularly CD film, enables very good photographic penetration of water. Underwater terrain contours and obstacles can be recognized and mapped by this CD photography, enabling offshore beach or shallow-water charting for amphibious operations.

Objects in shadow or shade usually are not detectable on normal black-and-white images, but they stand out readily on CD film. Objects of different colors, which usually show the same shades of gray in black-and-white photography, have definite color contrasts when imaged on CD film. This is especially valuable during conditions of low sun angle or in oblique photography where long shadows are produced.

CD photography is best reproduced and evaluated as transparencies, since the full-color values cannot be duplicated on paper prints.

2.1 Polarized Light Photography

In real target-background situations, illumination is by both direct sunlight and diffused skylight. Light reflected from surfaces, in turn, is both coherent and incoherent. Light reflected from most surfaces is considered partially coherent, in that a rough textured reflecting surface is a fairly good diffuser since the surface as a whole reflects diffusely while the many small facets of which it is composed reflect specularly. The expression $\frac{\sigma}{\lambda}$, where σ is the rms surface roughness and λ is the wavelength of the incident light, can be stated as a measure of the light-diffusing property of the surface. Multi-reflected light, in the case of a many-faceted rough surface, is randomly polarized. The intensity ratio of multi-reflected to directly reflected light is dependent on the distribution of facet orientation. This ratio generally increases with increasing total reflectance. Hence the degree of linear polarization of light reflected from diffusing surfaces is inversely related to the total reflectance.

The Naval Weapons Center, China Lake, California, has conducted many polarized photography experiments on natural terrain and man-made surfaces. Their experiments verify this relationship and prove that polarization contrasts can be used to detect and discriminate background and target materials, in both direct and diffuse illuminations. Several of their reports present a wide variety of natural materials photographed in both the visible and near-infrared spectrum. It was found that the largest polarization contrast exists in the 500 to 700 and the 800 to 1000 mμ region of the spectrum.

In general it can be stated that polarization contrast, like chromatic and luminous contrast, can be observed for any material, and that a discrimination capability is therefore present in the degree of polarization of light reflected from objects in any scene. Airborne measurements were carried out at NWC using a variety of polarizing filters in aerial cameras, and a polarizing TV camera was used in ground-based experiments.

2.5 Infrared Photography

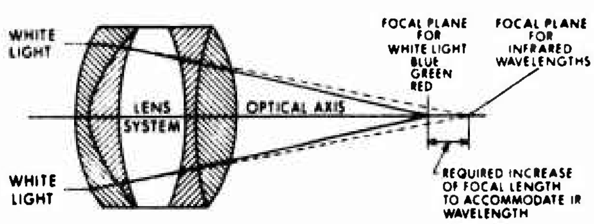
The use of black-and-white infrared film in aerial cameras has both advantages and disadvantages. This film is designed to be sensitive in the red and near-infrared wavelength region, but it is also sensitive in the ultraviolet region below 530 mμ. So that only the red and infrared portions will be recorded, a Kodak 89B filter is used to eliminate the ultraviolet and almost all the visible portion of the spectrum below 700 mμ.

The difference in black-and-white IR photography as compared to panchromatic is most evident in the recording of water and foliage, as reported from Navy studies (Naval Reconnaissance and Tech. Support Center, 1966). Since water does not reflect or transmit infrared radiation, and the blue portion of the rest of the spectrum reflected from water surfaces is filtered out, water appears very dark or black with respect to land which is a lighter gray tone. Grass, bare earth, and water might all show an equal density or gray tone on panchromatic film. However, IR film will show the grass as light gray and earth as medium gray, enabling ready distinction. Delineation of shoreline contours is an immediately obvious capability.

IR films record healthy, lush vegetation in the lightest tones,while vegetation that does not have enough water reflects less infrared energy and shows as medium tones, due to changes in the relative amount of chlorophyl and pigments.

The filtered infrared sensitivity of this film also makes it useful for haze penetration, since the less-scattered rays are recorded. This infrared sensitivity also provides increased tonal contrast between man-made and natural objects, such as an asphalt runway against an adjacent grass or soil background.

The resolution of black-and-white IR film is noticably poorer than panchromatic. Most lenses for aerial cameras are designed for visible light and therefore focus the infrared rays behind the normal focal plane, as shown in Figure 17.



LENS SYSTEM (CHROMATIC CORRECTED) FOCUSSES THE VISIBLE COLORS, BLUE, GREEN, AND RED LIGHT TO A COMMON FOCUS. TO FOCUS INFRARED WAVELENGTHS THE IMAGE FOCAL DISTANCE MUST BE EXTENDED.

Figure 17. Focus of Infrared Wavelengths With Focal Distance

Refocusing or lengthening of the focal distance is therefore required with IR film. Not all of the IR wavelengths will be brought into the film plane, but a sufficient portion of them will fall into focus to produce an acceptable image. The 89B filter provides a bandpass of 200 mμ to minimize the possibility of degraded images generated by the lens-film combination.

A photometer or exposure meter cannot give reliable values to determine proper IR film exposure, since wavelengths beyond the visible spectrum do not register on these devices. The usual technique is to use the manufacturer's exposure index as modified by the appropriate filter factor. Areas highly reflective in the infrared, such as vegetation, require less exposure than industrial areas. Examples of comparison of simultaneous panchromatic and IR photography are shown in Figure 18.

BLACK AND WHITE IR

PLUS X

Figure 18. Comparison of Visible and Infrared Photography

3. INFRARED SCANNERS

In the last decade, an airborne, electromechanical, imaging, infrared radiometer, generally called an IR scanner, has been widely used for reconnaissance. They are now proving valuable for gathering geophysical data inasmuch as they generate a two-dimensional thermal map indicative of surface or sub-surface parameters.

The earth radiates energy in a spectrum approximating that of a blackbody at 300°K, with a maximum near 9.5 μ wavelength. It also reflects solar energy whose spectrum approximates a blackbody at 6000°K with a maximum near 0.5 μ. The energy emitted by or reflected from the earth's surface is selectively absorbed by the atmosphere, with only the part that passes through "atmospheric windows" reaching an airborne detector, as shown in Figure 19.

In a scanner these detectors, generally sensitive to radiation between 3 and 5 μ or between 8 and 14 μ, as shown in Figure 20, convert the radiation into wide-band electrical signals that modulate a light source or cathode ray tube. Recording is generally made on film passing in front of the tube at a rate proportional to the velocity height ratio of the aircraft. Lateral coverage is provided by rotation of a collecting mirror, and forward coverage by the motion of the aircraft. The resulting image gray scale is thus a function of the detected earth surface temperature. Tape recording of scanner output enables preserving a higher dynamic range of imagery for enhanced evaluation.

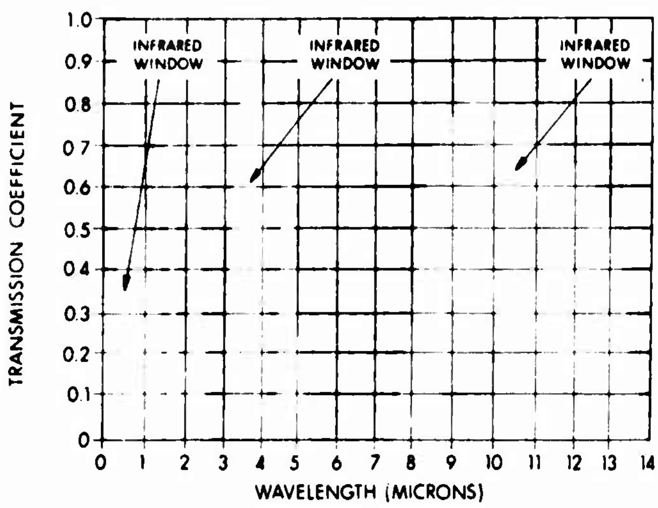


Figure 19. Infrared Transmission Through the Atmospheric Windows

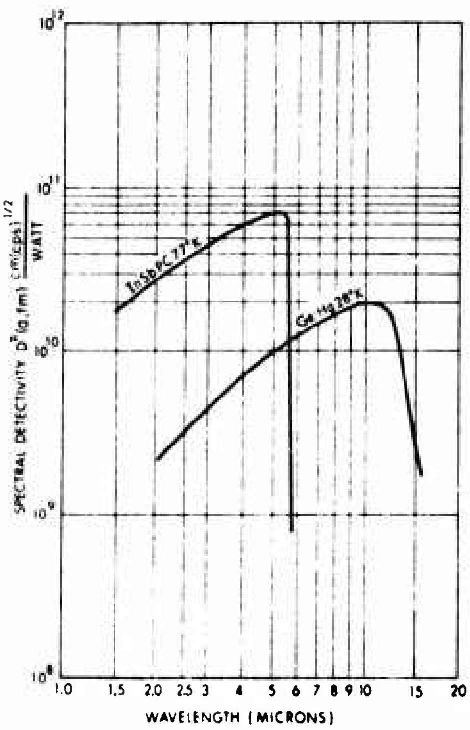


Figure 20. Infrared Detector Sensitivity Variation With Wavelength

Development of infrared scanners was pioneered by the University of Michigan, Texas Instruments, Inc., and HRB-Singer, Inc. Many terrain surveys using infrared scanning are being conducted by AFCRL, USGS, NASA, ONR, and ATSC (CRREL). Examples of such programs are thermal mapping of soil properties, vegetation, fresh- and salt-water ice patterns, volcanic activity, forest fire distribution, crevasses in ice, and recent applications to archaeology. The obvious military reconnaissance and detection programs using this technique are beyond the scope of this report.

Typical infrared scanner imagery obtained by AFCRL for terrain evaluation purposes is shown in Figure 21.

4. ULTRAVIOLET SENSING TECHNIQUES

A generally held opinion is that the absorption of solar radiation by the ozone in the earth's atmosphere causes a nearly complete attenuation of ultraviolet energy. However, experiments have proved that sufficient ultraviolet light may be available for daylight photography using sensitive film and appropriate filters. Also, it has been proved that many terrestrial materials have selective responses to narrow-band ultraviolet illumination.

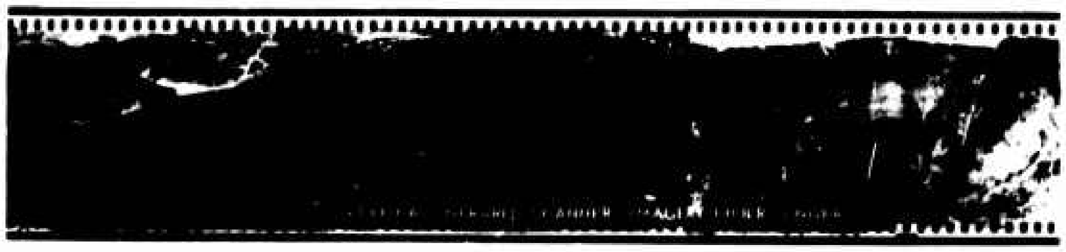


Figure 21. Typical Infrared Scan Imagery

AFCRL, AFAL, USGS, ATSC, and the Army Tank Automotive Center are government agencies that have performed experimental photography using ultraviolet transmitting filters to distinguish targets and terrain backgrounds. Texas Instruments, Inc., has done similar studies for material discrimination. AFCRL is incorporating an ultraviolet-transmitting lens in its aerial multispectral camera for airborne terrain surveys.

A promising application is being conducted by USGS (Hemphill and Vickers, 1966a) involving use of an ultraviolet video imaging system for detection of luminescent minerals and rocks and for possible discrimination among non-luminescing materials on the basis of selective absorption of energy between 330 and 410 mμ wavelengths. Their scanning system employs an S-11 photomultiplier detector and is filtered to accept only wavelengths shorter than 410 mμ.

Airborne scanning imagery in the ultraviolet has been collected by USGS from up to 15,000-ft altitudes over representative test sites (Hemphill, 1966b) and it shows distinct contrasts between materials and vegetation. Sandstone and carbonate materials with a minimum amount of moisture are particularly reflective in the ultraviolet.

5. PHOTOMETRY AND SPECTROMETRY

Data on the visible and near-infrared spectral reflectance of various elements of the earth's surface are of the utmost value in photointerpretation. These data can permit discrimination of materials by their tonal brightness appearance on aerial photographs. In addition, spectral reflectance measurements from field or airborne sensors, extending into the far infrared in some instances, allow determination of the mineralogy, chemistry, particle size, and surface roughness of materials.

Reflectance measurements are made by a variety of photometers, spectrometers, spectrophotometers, and radiometers, usually filtered for narrow-band outputs.

One of the earliest and still most comprehensive experimental studies of reflectance was published by Krinov in 1953. The National Bureau of Standards long-time work by Keegan and his associates on vegetation reflectance (Keegan et al, 1956; Gates et al, 1965) have been major references in the United States. Since then many organizations (MERDC, ATAC, AFCRL, NWC, and NASA) have conducted extensive measurements of rocks, soil, vegetation, and man-made substances. A chart compiled by the University of Michigan is given in Table 1. The compilation by Steiner and Gutermann (1966) is a valuable survey of Russian data since the original Krinov studies.

Under NASA Support, R. J. P. Lyon of Stanford (Lyon and Patterson, 1966) pioneered the gathering and interpretation of geological reflectance signatures in the 8 to 13 μ infrared region. By matching the measured signatures with predetermined ones in the memory of a computer, rock composition can easily be identified in field operations. Real-time determination at rates up to seven signatures per second, utilizing a filter wheel, are feasible, permitting sensing from aircraft. A typical group of emissivity signatures gathered by Lyon are shown in Figure 22.

6. RADAR SENSING TECHNIQUES

High-resolution, side-looking radar in the present state-of-the-art can be extremely useful for airborne determination of local geologic features, particularly geomorphic and gross relief patterns. A beam of radar energy provides unidirectional illumination rather than the multidirectional illumination given by atmospherically diffused sunlight. It therefore produces imagery that is composed of a great number of specular reflections, as the relationship of the surfaces to each other has a strong influence on the intensity of the returned energy recorded on the film. Small variations in surface relief thus imaged may express geologic phenomena such as folding, faulting, and drainage channels. Similarly, surface reflective characteristics based on the relationship of surface roughness to the radar wavelength can reveal to the interpreter the probable physical characteristics of the material. Fine materials such as clay, silt, or sand are imaged as a "no return", while coarser material such as rocks, a talus slope, or a lava flow show strongly textured patterns. Examples of such radar images are given in Figure 23, with interpretative captions, as reported by Autometrics Corp. (Bienvenu and Pascucci, 1962; Moore, 1966).

Table 1. Reflectance of Terrain Conditions

Type	Reflectance %	Peak Wavelength λ (μ)
Water Surfaces		
Inland Waters	3-10	0.4810
Oceans	3-7	0.4810
Bare Areas and Soils		
Snow	70-86	0.4810
Ice	75	0.5795
Limestone	63	0.5790
Calcareous Rocks	30	0.5790
Granite	12	
Mountain Tops (Bare)	24	0.5816
Sand	18-31	0.5616
Clay Soil	1.5-15	0.5828
Ground Bare (Rich Soil)	7.5-20	0.5832
Field (Plowed)	20-25	
Vegetative Formations		
Coniferous Forest	3-10	0.5744-0.5758
Deciduous Forest	10-15	0.5719-0.5858
Meadow (Dry Grass)	3-8	0.5758
Grass (Lush)	15-25	0.5719
Field Crops	7-15	0.5858
Man Made		
Buildings (Cities)	9	0.5828
Concrete	15-35	

Although the resolution and definition of side-looking radar images are much poorer than aerial photography, radar has many operational advantages over the latter. Returns can be obtained through any weather conditions except heavy rain; the day- and night-scanned images are equally good; returns can be obtained from high altitude and at high speeds; coverage extends many miles to either side of the aircraft; and the scale is built into the system.

There are two types of imaging radar, the noncoherent or real aperture type of system that uses a large antenna, and the coherent or synthetic aperture type employing a relatively small antenna along with an elegant signal processor. Both are generally used in a direct side-looking aspect. With noncoherent radar,

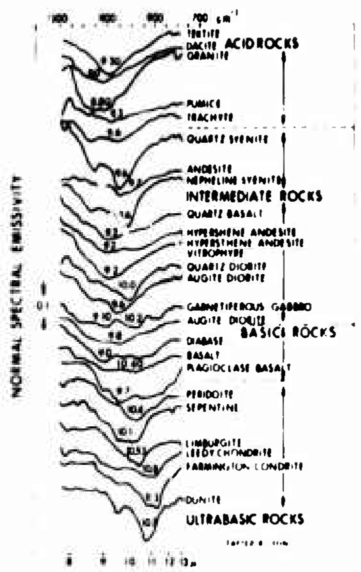


Figure 22. Spectral Emissivity of Common Rocks (Lyon and Patterson, 1966)

Figure 23.
Radar Imagery

resolution is determined by the antenna beamwidth; with coherent radar, resolution is achieved by the processor's ability to separate targets closely spaced in azimuth by virtue of their time-displaced doppler histories.

Synthetic aperture imaging systems function as follows: The aircraft carries a small side-looking antenna producing a fairly broad beam that scans the terrain by virtue of aircraft motion. The terrain is illuminated at an appropriate sampling frequency by either a narrow pulse or a pulse-compression waveform, depending on the resolution and range requirements. The reflected signal, after intermodulation with the coherent transmitter reference, is stored. Successive terrain-signal samples are then processed in a manner analogous to the coherent weighted summation carried out by a large antenna array. The actual signal processing is usually carried out by optical methods involving film as the storage medium; however, real-time systems have been built using a storage tube as the memory and electronic circuitry for the matched-filter processing. The resolution of a synthetic aperture radar, in contrast to most sensors and optical devices, is independent of range as long as an adequate signal-to-noise ratio exists.

Radar imaging provides location as well as magnitude of the back-scattered return. Because imaging systems operate over a rather restricted portion of the RF spectrum and towards the higher end (typically X and K bands), more is determined about the geometry of a radar target as opposed to its properties as a radar reflector.

Most modern side-looking radar systems are classified as to their specifications and operating parameters, and their use for reconnaissance and target detection purposes is well known and beyond the scope of this report.

A non-imaging four-band radar system has been used by the Army Engineer Waterways Experiment Station for several years in investigations of the radar power return as functions of soil properties. The system comprised K-, X-, C-, and P-band frequencies beamed on soil samples from a 50-ft elevation at various incident angles, as shown in Figure 24. Test conclusions were that such radar

Figure 24. Army WES Experimental Radar System

sensors can provide information on surface water and moisture content of deep homogeneous soil samples. In addition, a swept-frequency radar system can locate ground or surface water. Research investigations are now being conducted for boom-mounted instruments carried on ground vehicles transversing natural terrain.

Stereoscopic or three-D radar is still in the research stage, and several commercial electronic organizations are in the process of developing feasible systems.

Such newer developments have not downgraded the use of high-definition radarscope photography for studying the earth's surface. Detailed analysis of such imagery has been reported by Texas Instruments (Feder, 1960) and by Acadia University (Cameron, 1965); their analysis shows marked delineation of fracture patterns, folds, and faulting, and distinct erosional patterns.

Optical radar, laser radar, opdar, and lidar are terms applied to the use of narrow-band or coherent light propagation and return similar to conventional radar. Many organizations are conducting research on these techniques, but to date they are used mainly for detection and ranging purposes. Identification and measurement of earth properties and characteristics by such coherent-light beam is still an application awaiting further study.

6.1 Pulsed Radar Techniques

Instantaneous airborne determination of the thickness or layering of terrain material, especially floating ice, is feasible by use of high-resolution, monocycle radar. The analogy is to seismic-reflection prospecting using a single acoustic pulse, in that a single electromagnetic pulse (monocycle) is radiated into the terrain and thickness determined by analysis of the reflected returns.

When a monocycle is transmitted, a portion of the energy is reflected at the air-surface interface; the remainder is transmitted through the medium, and some of this is again reflected at the next interface. The latter might be a layer of soil having a different density or moisture content, such as the water table, the top of bedrock or permafrost, or the ice-water interface of floating ice sheets. Matching of the relative pulse amplitude and time delay to patterns prepared for the known physical properties of the medium being surveyed enables determination of the thickness or layering depth.

The period of the pulse is determined by the resolution required or the frequency range desirable. In general the lower frequencies can penetrate more deeply with less scattering, but at the same time are limited in time resolution for return signal interpretation. Pulses with central frequency of 400 megacycles and periods of several nanoseconds have successfully been used for this type of terrain sensing.

Barringer Research, Ltd. (Barringer, 1965) developed and tested such a system, using shock-excited antennas on a ground vehicle boom as shown in Figure 25, which accurately determined the thickness of the lake ice to within 10 percent.

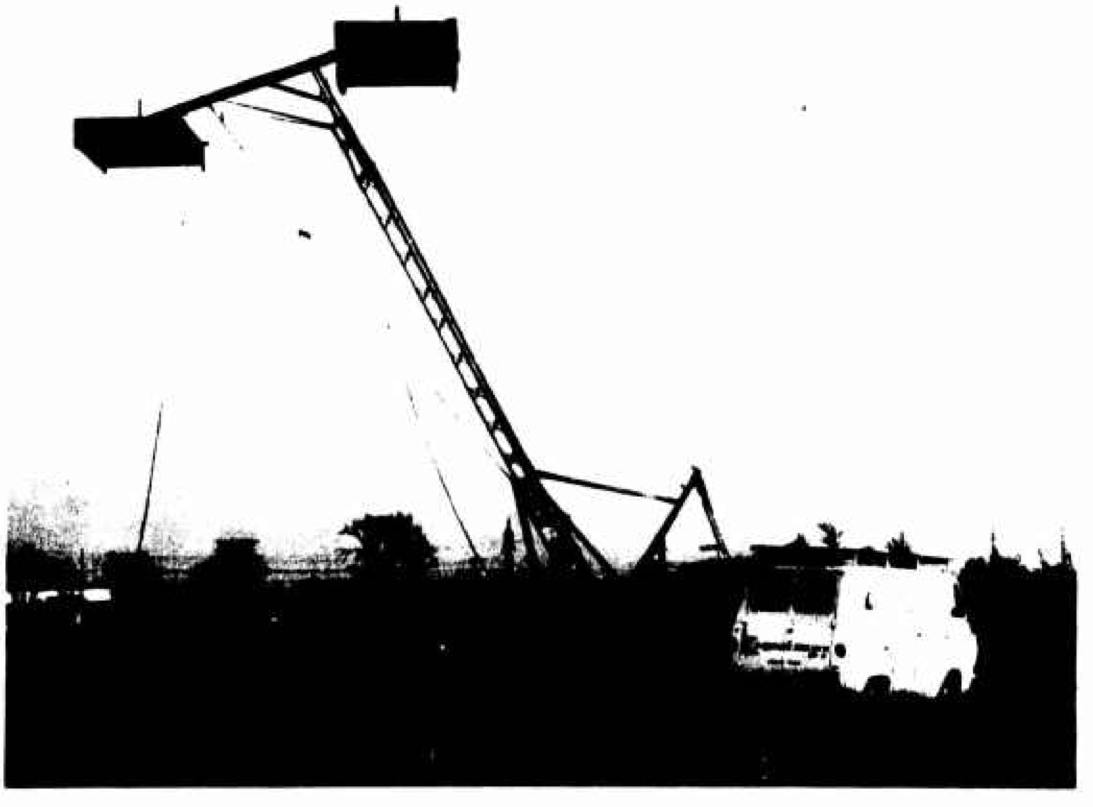


Figure 25. Pulsed Radio Wave Method

Thickness and layering measurements of soils were less successful, due to the complex dielectric constant and conductivity relations within a soil mass. Additional tests indicated that variable-frequency radar operating at frequencies between 100 and 300 MHz, together with coincidence and correlation analysis of the complex pulse returns by computer techniques, would provide this capability. Barringer Research, Ltd. has recently developed an airborne version of this system for NASA that is awaiting verification tests. The Army Engineer Waterways Experiment Station has continued the work on the variable-frequency concept, using 300 MHz

frequencies on multi-layer soil samples. Absolute values of the soil dielectric constant were determined and the thickness of soil layers measured, even though the reflected power dropped to less than one percent due to surface roughness scattering or vegetation attenuation. Field tests by a ground vehicle-boom configuration are now being conducted.

The Adcole Corporation, under contract to the Army Terrestrial Science Center, has successfully continued the ice-thickness measurements, using a monocycle radar system from a helicopter (Meyer, 1966). Fresh-water ice masses up to a meter thick were measured, even with one-half meter of snow cover.

6.2 Radar Scatterometry

Radar scatterometry is an active remote-sensing technique pioneered by Dr. R. K. Moore at the University of Kansas under NASA sponsorship (Moore, 1966). It measures the radar scattering coefficient of surfaces having different roughness and material. Applications to measuring sea state and ice roughness were established, and indications of terrain texture and moisture content, both at the surface and somewhat beneath it, were observed. Scatterometry is feasible with wavelengths from fractions of a micron (using lasers) to tens of meters. The normal range for radar scatterometers is from a few millimeters to a few meters wavelength. This range by comparison is wider than from violet light to the longest infrared wavelength commonly in use.

Signals generated by a radar transmitter are re-radiated from the ground and received back at the radar location. If the ground surface is a perfectly smooth plane or sphere, a specular reflection results. Such surfaces almost never exist in nature, hence radar return is almost always a scattering process, enabling measurement of the scattering or reflectivity coefficient. The most favorable angle of incidence of an airborne radar scatterometer is near zero (normal incidence), as with larger angles the range is so great that signal return becomes too small for processing.

Normally, the radar scatterometer cannot discriminate individual small elements of the surface, but must look at a sum of the returns from many such elements. Processing of the data enables compilation of the differential scattering cross section that describes the average properties of a particular surface type.

Conclusions from experimental data gathered by the University of Kansas and Ohio State University with airborne radar scatterometers are that relatively smooth surfaces, such as the ocean, give strong returns near the vertical but the returns fall off rapidly with angle. Surfaces having the same geometry as the sea surface, but smaller reflection coefficients, such as deserts, have scattering coefficient curves with the same shape but smaller absolute magnitude. Surfaces

rough compared with wavelength, such as forests, or, for very short wavelengths, rough gravels, have smaller scattering coefficients near the vertical than the smoother surfaces. However, their scatter changes little with angle, so that near grazing the return from the rough surface is much greater than that from the smooth surface.

Both experimental observations and theory indicate that returns near the vertical are due to larger scale fluctuations in the surface than the returns near grazing angle of incidence. Detailed curves for specific materials have been prepared, including vegetated surfaces. Radar scatterometers provide their own illumination and can, therefore, discriminate among returning signals that are not dependent on self-emission or randomly incident sources reflected from the surface.

7. IMAGERY ANALYSIS TECHNIQUES

Skilled interpretation of sensor imagery, particularly photography but also including infrared-scanner and side-looking radar imagery, is the standard and most widely used method for identifying and evaluating earth surface features. The variation of the individual ability and experience of photointerpreters obviously affects imagery analysis, and efforts to improve upon such often subjective techniques are a necessity. Photointerpretation has generated a great variety of coding keys of terrain and cultural features, signatures, and backgrounds. However, these keys are used mainly to help an interpreter discriminate targets from the terrain background, whereas the objectives of remote sensing, as indicated in this report, are to provide knowledge of the properties of the "background" itself.

The University of Michigan is conducting (for the Air Force Avionics Laboratory) a target-signature program wherein they will compile, tabulate, and evaluate as much electromagnetic sensor imagery as possible pertaining to target discrimination and terrain characteristics. The NASA Manned Spacecraft Center in its Earth Resources program has also accumulated a vast library of sensor records of the character and composition of landforms and features of the earth's surface.

Many techniques are in the process of development, test, and application to ease the problems of manual interpretation of large amounts of sensor imagery and returns. Recording on magnetic tape allows a larger dynamic range of input signals and facilitates later processing of such imagery for enhancement of detail and contrast. The use of thermoplastic tape, pioneered by the General Electric Company, allows real-time recording up to densities of 1700 lines per inch with picture elements of 8000 per line (AFAL, 1966). The recording is done by an electron beam writing on a strip of 70-mm thermoplastic tape.

Electronic instrumentation for scanning imagery now permits the presentation in a graphical form of the gray-scale tonal values along the scanned traverse. Such waveform segments can be presented as statistical parameters associated with the various terrain types or characteristics recorded on the image. Many commercial and university groups have published descriptions and uses of such instrumentation for pattern-recognition objectives.

The color enhancement or color-additive technique is an excellent tool in photographic imagery analysis, particularly with multispectral images. Using this technique, for example, a negative is prepared from band 1 and a positive from band 2. By superimposing these, a complete cancellation is achieved except — a highly significant point — for those areas where a color difference exists in nature. A more sophisticated step is to prepare various combinations using many bands, such as a red, a blue, and a yellow band. In each case the film records emphasize color difference and subdue color likeness. When these records are cascaded and printed as a single unit or with additive printing onto a final color positive, the resulting image brings out features indistinguishable in any of the original film records. The appearance is that of a camouflage-detection image, and it emphasizes the otherwise subtle tonal differences discerned by the camera.

Optical data processing is a relatively new method that enables extraction of detail and contrast from photographic negatives. The development of fiber optics and the laser has sparked many applications of digital optical systems to data processing, pattern recognition, and analog computation. A major advantage of digital optical systems is their high storage density. Such systems enable the obtaining of many successive two-dimensional Fourier transforms of any given light-amplitude distribution, such as would be represented in aerial photographs of the earth's surface. The applications of optical data processing to geologic imagery interpretation and enhancement is currently under study for AFCRL by the University of Michigan. The appreciation of the imaging properties and vast storage density of holograms is an outgrowth of these experimental studies of reconstruction and analysis of imagery. However, lack of qualitative measurements and limiting conditions of image reconstruction have handicapped the use of holography, except in the laboratory.

Change detection, or the analysis of differences between two sets of imagery taken of the same area at different times, can show such factors as seasonal effects on terrain, growth of vegetation, and the sequential morphology of landforms, in addition to the militarily important changes in man-made or cultural features. Photographic or electronic images can be scanned, rectified, manipulated, and correlated by existing techniques, and evident changes can be automatically compared and recorded.

The Army Engineer Topographic Laboratory has developed an "automatic mosaicker" that produces rectified transparencies from imagery and compares them for change-detection purposes, rejecting extraneous factors such as clouds and shadows. Vertical images obviously have the greatest potential for treatment and analysis by this technique. Further extension of the change-detection concept to the "moving target indicator" are well developed and generally used in radar and active sensor reconnaissance and will not be treated in this report.

8. PASSIVE MICROWAVE RADIOMETRY

All objects emit electromagnetic energy due to the random thermal agitation of the electrons within them. The intensity of this radiation depends on the temperature of the object, the frequency at which it is measured, and certain of its physical properties such as dielectric constant, magnetic permeability, electrical conductivity, and surface characteristics. An object may also absorb or reflect any electromagnetic radiation that is incident upon it. The radiometric temperature of an object thus not only is dependent on its emissivity and own temperature but also on its reflectivity and the temperature of the sky environment being reflected.

The radiometric energy emitted from an object or material can be measured at great distances. In the microwave and millimeter wavelength regions the power emitted varies directly with its temperature and inversely with the square of the wavelength. At a given frequency and polarization the emissivity and reflectivity of a material are functions of its surface roughness and the angle of incidence of the radiometer antenna. The region of a solid object that contributes to its observed radiometric temperature extends from the surface downward to a depth depending on its dielectric constant and conductivity. Different frequencies can therefore be said to have different penetrations. Materials such as water or metals have high reflectivities and generally exhibit cold radiometric temperatures (150^{o}K). Conversely, good absorbers such as dry soils or vegetation show high radiometric temperatures (290^{o}K).

Passive microwave radiometric sensing of the apparent temperature of natural terrain and objects upon it is a previously neglected technique. With the development of new analytical methods, advanced instrumentation, and data processing techniques, this sensing method can now be effectively employed for ground-based and airborne earth-science studies. Raytheon Corp., North American Aviation, Inc., and the Jet Propulsion Laboratory of the University of California have used microwave sensing for several years and reported extensively on its applications.

Probably the most comprehensive application of passive microwave sensing of the properties of terrain is being conducted by the Space General Division of Aerojet General Corporation in a tri-service-supported study (Kennedy et al, 1967; Kennedy and Edgerton, 1967). From a boom on an extensively instrumented trailer, a three-frequency microwave radiometer with both vertical and horizontal polarization capability was successfully used to determine the moisture content, layering, and distribution of soils, water, ice, snow, and rocks. An example of the discrimination of soil types on the basis of their radiometric temperatures thus obtained is shown in Figure 26. Soil moisture content can be identified to a 1 percent accuracy by this technique.

Airborne passive microwave radiometric sensing is also a valid technique. Test flights of one of the Space General Division's radiometers over the terrain previously studied have closely verified the previous measurements. Icebergs and floating sea ice were detected by the U. S. Coast Guard for several years, using microwave equipment developed by Sperry Rand (Roeder, 1967).

Microwave thermal imaging of terrain is still a technique awaiting advanced equipment development. Space General conducted experiments using a 3.2-mm (94 GHz) radiometer (Chalfin and Ricketts, 1966). The output, as recorded on magnetic tape, was processed by a computer and plotted to yield half-tone images. Although appearing crude to the eye trained for photographic-image analysis, they showed gross terrain features that closely corresponded to visible-light photographs. The contrasts between reflectors and absorbers was strong, and in heavy fog, where visible and infrared photographs showed practically nothing, a useable image was produced by the radiometer.

9. VAPOR AND TRACE MATERIAL SENSING

Remote sensing of odors, gases, and vapors has recently been applied for personnel detection by the "people sniffer" developed by the Army Limited War Laboratory, and successfully used in Viet Nam. Another obvious use of such a technique is the conduction of air pollution studies. The measurement of vapor concentration by remote sensing is also potentially useful for geophysical exploration. Geothermal and volcanic activity often give rise to emanations of sulphur dioxide and halogens in the air, which can readily be of significance as indicators of sources of power, heat, and minerals, as well as potential hazards to military or geophysical installations.

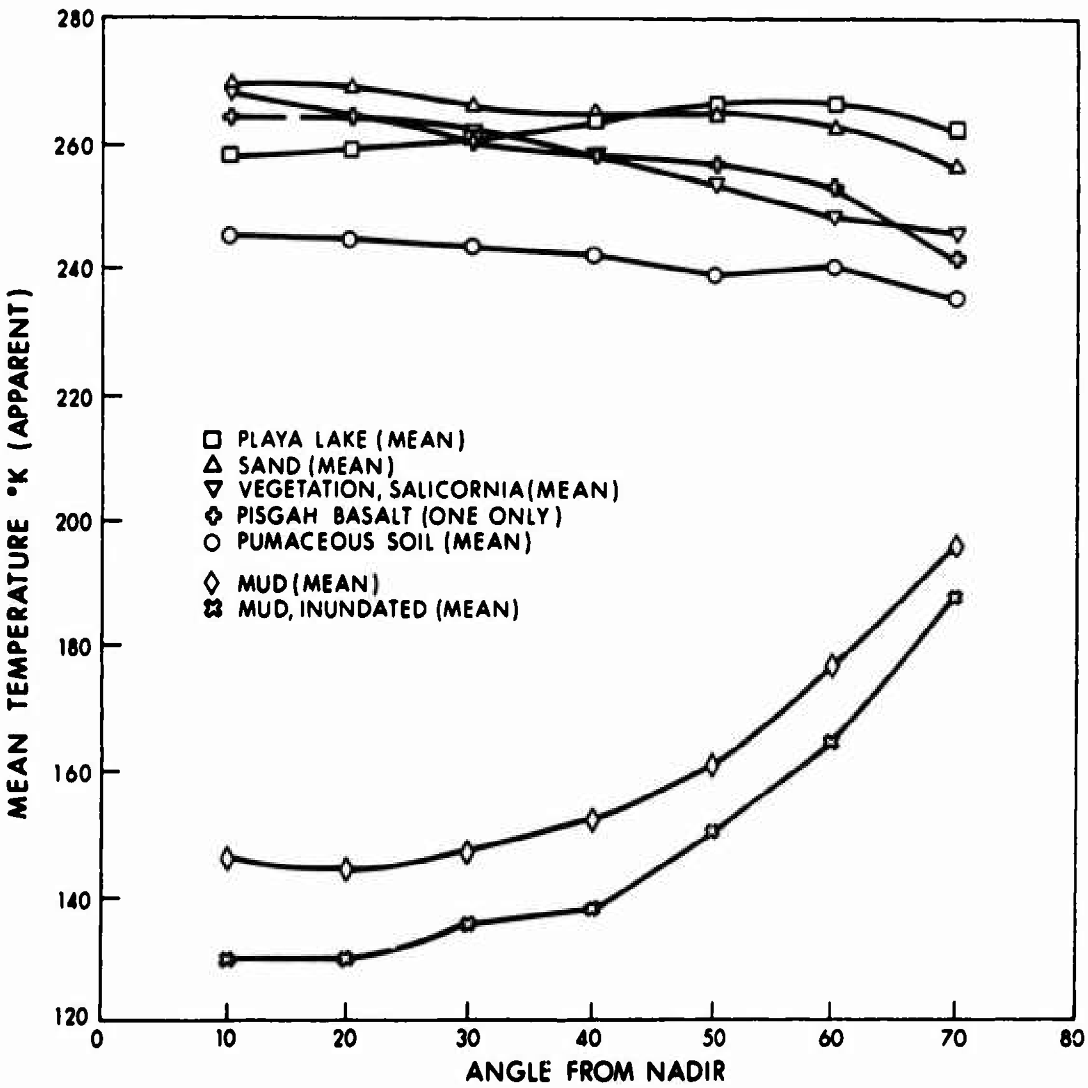


Figure 26. Passive Microwave Data on Various Natural Materials

Oxidizing ore deposits similarly generate vapors that might be detectable. The association of detectable iodine with deposits of marine origin, such as oil field brines, may be exploited. Iodine is also concentrated in marine organisms and plant life by a factor of 10^5 as compared to seawater. Such sensing of marine life could have important economic applications in the future.

Barringer Research, Ltd. developed and tested instrumentation for the remote sensing of vapors; the instrumentation has a sensitivity in the one part per billion range (Barringer and Shock, 1966). The design is based on a conventional spectrometer with its exit slit replaced by a "spectrum correlation" recording mask. These masks are pre-prepared for known gases or vapors and used to cross-correlate the maxima and minima absorption bands of incident light from the gas being sampled. Laboratory tests have verified the sensitivity of the instrumentation and the feasibility of detecting and identifying low concentrations of sulphur dioxide, mercury, and iodine. An airborne unit has been built for NASA. It features an automated mask changer which programs the device for a number of specific vapors to be sensed and identified. Very high sensitivity for monotomic vapors can be obtained, due to the strong and narrow absorption lines they produce in a spectrometer.

The Army Ballistic Research Laboratory developed techniques for the rapid interpretation and discrimination of characteristic chemical vapor signatures by computerized pattern analysis. Such a system might be used with suitable sensors in low-flying aircraft to collect information about ground sources of such material.

10. LASER APPLICATIONS

So that low-light-level TV or scanning sensors can be used at night to view terrain or targets, laser illumination techniques are under development and even now being tested in actual operations. Such lasers radiate mainly in the infrared region. Problems foreseen are the need for stabilized systems to overcome aircraft buffeting by turbulance and the possible degradation of laser illumination by dust, smoke, or clouds. Also, the high repetition rates of a laser illuminator require more reliable and better cooling systems than do less sophisticated scanning assists.

A laser line-scanning camera used as a hightime reconnaissance sensor has been extensively tested (Stein, 1967). Such a sensor uses a laser beam scanned at right angles to the aircraft flight direction as a light source to illuminate the terrain below. The laser returns, varying as a function of the terrain reflectivity, are recorded on film with very high quality imagery resulting. Such a system eliminates the need for flash cartridges or other giveaways of the position of the photographic aircraft.

11. AIRBORNE PROFILE RECORDERS

The microtopography or surface roughness of terrain is of obvious importance in planning or conducting military operations. Natural obstacles such as bushes, boulders, or gullies complicate the evaluation of normal slope variations. When Arctic regions are considered, the ever-present pressure ridges and the irregularities of sea ice, glaciers, and ice fields are natural hindrances to wheeled vehicle traffic. Other needs for airborne surface roughness measurement are information on sea state conditions, wave heights, beach slopes, etc.

For many years, combinations of radar and barometric altimeters were used for relative terrain height measurements. These devices, commonly called airborne profile recorders, use the principle of radar reflection over aircraft-to-terrain distances, corrected for aircraft altitude deviation from some barometric datum surface. A reference is established by flying at a pre-set barometric altitude over a terrain feature of known elevation. Further flying over an area of interest will enable applying the aircraft altitude deviation to the radar height record to give the terrain profile. Primary limitations are accuracy (about 1 ft ± 0.5 percent of flight altitude) and beam size (15° half angle). Present narrow-beam airborne profile recorders are estimated to have an accuracy of ± 20 ft at altitudes up to 30,000 ft, while illuminating an area 500 ft wide.

A recent joint development of Aero Service Corp. and Spectra-Physics, Inc. has provided an operational laser altimeter with greatly improved accuracy and resolution performance (Jensen and Ruddock, 1965). This device incorporates an improved barometric pressure sensor with a CW helium-neon gas laser generating 50 mW of diffraction-limited light at 6238 Å. The beam generated is about 1 in. wide, resulting in terrain height resolution of 2 in. in the vertical plane and less than 1 ft in the horizontal at 1000 ft altitude, and within 2-5 ft vertical resolution at 15,000 ft altitude. Flight tests conducted under the auspices of the Army Engineer Waterways Experiment Station verified the exceptional ability of this device for terrain profiling. A limitation to all-weather use of this laser altimeter is the severe attenuation and scattering of the light beam by water vapor.

12. GAMMA-RAY SENSING

The gross natural gamma radioactivity of common sediments has been used for many years in mineral and oil exploration and in the interpretation of geologic structure. Marine shales have abnormally high radioactivity, whereas other rock types such as anhydrites, pure sandstones, and limestones have very low radioactivity.

The principal natural materials contributing to background gamma radiation are the uranium, thorium, and potassium decay series. Different soils and their parent rock material show varying and characteristic contents of these chemically different natural radioactive elements, which reflect the physics and chemistry of the rock in addition to the effects of weathering in soil production. In general, these element contents of igneous rocks increase with increasing acidity or silica content. These concentration ranges are tabulated in Table 2.

The U. S. Geological Survey (Moxham, 1960) has extensively explored mapped total gamma radio-activity patterns throughout the United States, using airborne scintillation counters. Major oil companies have done similar work in smaller areas. The recent development of practical, total-absorption, gamma ray, spectral-measuring equipment for field use has enabled much refinement of soil and rock identification by this technique.

The Army Engineer Waterways Experiment Station has conducted detailed laboratory investigations to determine soil parameters useful in estimating trafficability (USAEWES, 1967). Their results indicated that photopeak counts of the radioisotopes of primary interest were proportional to the moisture content of the soil samples; however, ratios of these photopeaks were nearly independent of moisture content, although different for each soil type tested. From this data, it would appear that geological formations, such as loess and shales, can be distinguished from limestone and sandstone material, and that this technique is a powerful tool for estimating soil moisture content. Airborne tests using a large array of gamma ray detectors were recently conducted to verify the extension of this sensing method for remote measurement.

13. AIRBORNE EM SENSING

Since a high proportion of the earth's sub-surface is covered by a mantle of soil, ice, weathered rocks, transported alluvium, glacial debris, dense vegetation, or water, airborne "prospecting" for subsurface deposits of minerals or strategic resources is limited to those deposits which have a surface expression. Airborne magnetic surveys are effective in outlining many types of intrusive and extrusive rocks, even when they are buried under deep overburden. However, these surveys are limited in defining the sedimentary geology wherein valuable ground water, non-magnetic metallic deposits, industrial minerals, construction materials, and oil resources may be residing.

Associated parameters such as conductivity, which can be sensed from aircraft, can provide useable clues to sub-surface deposits. The majority of metallic ores such as copper, nickel, lead, zinc, silver, and gold contain sufficient sulphides

Table 2. Radioactive Elements in Igneous Rocks and Sediments

RADIOACTIVE ELEMENTS IN IGNEOUS ROCKS			
Rock	Thorium (ppm)	Uranium (ppm)	Potassium (%K_2O)
Silicic Intrusive (Granites & Syenites)	1-25	1-6	1.5-6.0
Silicic Extrusive (Rhyolites & Trachytes)	9-25	2-7	
Basic Intrusive (Gabbros & Diabases)	0.5-5	0.3-2	0.4-3.0
Basic Extrusive (Basalts & Andesites	0.5-10	0.2-4	
Ultrabasic Intrusives (Peridotites & Dunites)	low	0.001-0.03	0.1-1.0
RADIOACTIVE ELEMENTS IN SEDIMENTS			
Rock Type			
Clastic Rocks			
Common Shales	2-47	1-13	0.9-6.7
Orthoquartzites	0.7-2	0.2-0.6	0.9-2.6
Black Shales	2.8-28	1.4-80	0.9-6.7
Residual Rocks			
Bauxites	8-132	1.5-22	very low
Bentonites	6-44	1.0-21	very low
Precipitated Rocks			
Carbonates	0.1-7	0.1-6.5	0.1-0.6
Salt Beds	0.4-0.5	1 -5	up to 30%
Chert	0.1-1.6	0.01-0.9	0.07-0.4

to provide them with a large conductivity contrast with surrounding rocks. The development of low-frequency, electromagnetic, inductive, airborne sensing systems has recently been exploited for commercial exploration. Present capabilities permit detection from several thousand feet altitude and signal penetrations up to 700 ft depth.

The U. S. Geological Survey is currently using an induced-pulse-transient EM system in an aircraft. This system radiates a short electromagnetic pulse that induces eddy currents in conductive bodies (Barringer, 1962). The pulse has a repetition rate of 380 pulses/sec, and is generated from a large horizontal loop antenna strung across the aircraft. The time-varying decay transients of the eddy currents are received in a stable high-drag "bird" towed behind the aircraft. The amplitudes of these received signals are sampled after selected time delays and their ratios define the shape of the characteristic decay curve associated with the degree of conductivity.

Initial use by the Canadian Geological Survey has indicated the ability of the system to detect gravel deposits, which could be important aquifers, lying in glacial clays (Collett, 1965). Computer analysis is being applied to study conductivity stratification in the ground. Results indicate that differentiation of areas of sulphide mineralization from those of other ionic conductors is feasible.

11. AIRBORNE MAGNETOMETERS

The airborne magnetometer has been used since 1946 in petroleum and mineral exploration, with some 20 million square miles of survey flown covering a large portion of the earth's surface. The military services have used airborne magnetometers for reconnaissance of submarines and land-vehicle targets. Gradual improvements in instrumentation have been made, but 1 gamma has generally represented the limit of attainable resolution.

Recently the rubidium vapor magnetometer was developed. Although originally designed to measure the magnetic field in space probes, it has had immediate use as an airborne device for oil exploration. The resolution of this device is 0.1 gamma, enabling more detailed mapping of the total magnetic field, which in turn reflects variations of the sedimentary structure and basement complex of the earth. The system can be located in a towed-bird configuration or mounted in a tail-boom "stinger" on aircraft. Data are presented on a strip chart in analog form, with the linear scale calibrated directly in gammas for easy compilation of area maps.

Further application of this new device has resulted in the magnetic gradiometer (Aero Service Corp., 1967), an ultra-sensitive tool for direct measurement of the vertical gradient of the earth's magnetic field. This system comprises two

simultaneously recording rubidium or cesium vapor magnetic sensors flown from or on an aircraft and separated by a fixed vertical distance. Sensitivity of measurement of the vertical gradient is in ten-thousands of a gamma per foot. In comparison to the total field map, the gradiometer more closely defines and differentiates earth structure effects and increases the amplitude of local anomalies while attenuating regional effects.

These new magnetometers also have application to the detection of buried objects, when used in ground-vehicle surveys. Arms caches, pipe lines, underground communication cables, etc., are susceptible to detection by this method, and it has been used recently in a presently inconclusive attempt to detect tunnels in Vietnam. Previous applications in detecting buried materials for archeological purposes have been reported.

15. GRAVITY SURVEYS

While airborne or surface measurement of the variations of the gravitational field over terrain areas cannot directly reveal the surface properties of such areas, these variations are often indicative of the geological formation beneath. In general, without delving into complex theories of gravity-earth structure relationships, it can be said that gravitational anomalies are related to the densities of underlying material. The average density of granitic rocks is about 2.7 gm/cc; for poorly-sorted fans and alluvial debris it is 2.4 gm/cc, and for silts, clays, or other fine material it is 2.0 gm/cc. Detailed surface gravity surveys may, therefore, give useful information on basement topography, the depth and extent of basin or fill material, the presence of faults as inferred from steep gravity gradients, and barriers to or channels for ground-water movement. In addition, sub-surface cavities or voids can be easily detected, since they appear as "negative" gravity anomalities of substantial size and extent (Romberg, 1961).

Because of the higher altitude and speed of coverage, airborne gravimetric surveys have far less capability to distinguish the density of terrain areas. However, experimental airborne gravimetric surveys are often used by commercial petroleum companies to outline large geologic structures, such as salt domes, that could be oil-bearing formations. Other large-scale regional features such as deep crustal rifts, major deep-seated igneous rock intrusions, and massive ore deposits may similarly be detectable, using the recently developed gravity gradient sensors of extremely high sensitivity (0.1 mgal).

16. ACOUSTIC SENSING

Acoustic sensing techniques are generally typified by the use of sonar to identify the location and spatial configuration of underwater objects such as submarines, mines, reefs, or structures. Some application has been made to sounding the bottomside of floating ice from submarines. However, airborne use of acoustic sources as sensors of terrain properties is generally infeasible. Limiting factors include the scattering of the sound through the intervening atmosphere, the wide-beam coverage of such a source, the scattering of a possible return, and the lack of acoustic coupling for propagation of sound waves through unconsolidated soils.

Sonar mapping of ocean bottom sediments and their distribution has been successful, using acoustic sources from a ship. Information on landforms adjacent to lakes, fjords, or rivers might be gained from a knowledge of the erosional materials deposited as bottom sediments. Sonic techniques deployed from a hovering helicopter having the necessary electric power capacity might also be used. One such commercial system generates a 0.5 msec acoustic pulse with extremely high peak pressure and a frequency of 1000 Hz. The reflected pulses are recorded on a moving chart to provide a continuous vertical profile of bottom characteristics. Analysis of reflection losses, ranging from 10 percent for hard sand to 90 percent for mud, might aid in determining the type and density of the parent material.

17. SEISMIC EXPLORATION METHODS

Seismic techniques obviously cannot be used in an airborne mode, but they do have application for ground-based terrain surveys. The seismic refraction method can be used to determine the depth to interfaces such as the water table, permafrost, bed rock, or sub-surface formations offering a distinct change in the propagation velocity of seismic waves. Delineation of deep-lying deposits is possible and qualitative relationships between seismic velocity and hydrologic parameters such as porosity and density have been established. Mapping of buried aquifers is therefore practical.

Now available are compact portable seismographs that utilize a hammer blow against a steel plate on the ground as an energy source. This eliminates the need for drill holes and explosives, and has greatly enlarged the utility of operation.

Some identification of the type of near-surface material is possible from computation of the wave velocity obtained by a thorough seismic refraction survey (Linehan, 1951). Dry, wind-blown sand or fine gravels have velocities varying from 1500 to 2500 ft/sec; heavier gravels with small amounts of clay binder run

up to 4000 ft/sec; while velocities from 4500 to 6000 ft/sec represent more compact gravels or those within the water table. Varved clays show a constant velocity of 5000 ft/sec, while values from 6000 to 9000 ft/sec usually represent a hard pan or till material that is heavy gravel and clay, often cemented together by iron rust or oxidation.

Rock velocities are not as reliable indicators of type, but in general low seismic velocities are associated with less dense or lower strength rocks.

18. ELECTRICAL RESISTIVITY MEASUREMENTS

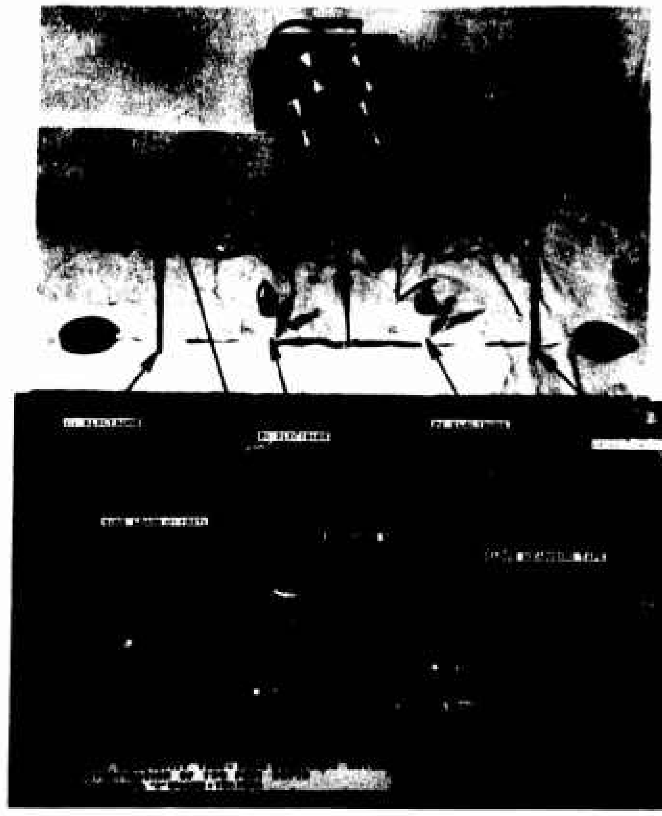
Sensing of terrain properties by analysis of electric current propagation through the ground is a well-established exploration technique. Active transmission methods are generally used in resistivity measurements, while passive recording of telluric currents also provides information on sub-surface conditions. It is not feasible to generate or record such currents from the air, so these techniques would have no application in airborne sensing. However, field exploration using ground vehicles might well use electrical methods.

All surface and sub-surface materials have to some degree the ability to conduct an electrical current. The moisture within the earth's materials and, more particularly, the impurities in this moisture provide an avenue for the current flow. It is natural for the harder, denser, rock layers (containing less moisture and perhaps less impurities than the clays and silty layers) to have higher resistivities than fine-grained clays or silt. Salt water is a very good conductor of current flow. Hence, a geologic layer such as shale or clay, laid down under marine action, usually has a very low resistivity. Such materials can be located beneath weathered or leached-out materials overlying them.

Usually, any hard, dense layer of parent rock will have a resistivity that is different from its weathered components. Because of these and other characteristics, trial and calibration must be made over exposed or identifiable formations of each material to produce the type curves needed to evaluate data obtained from exploration.

The distance between the electrodes is a function of the depth of the area surveyed, as shown in Figure 27. By increasing the spacing, the test can be carried deeper, and any deep formation, such as solid rock, having generally higher resistivity than the surface layer, will be indicated by a rapid rise of the plotted curve. Tabulation and interpretation of measured resistivities can establish relationships of these to porosity, texture, salinity, and mineral content of terrain, in addition to defining the depth of bed rock, the water table, or permafrost layers.

INSTRUMENTATION



THEORY

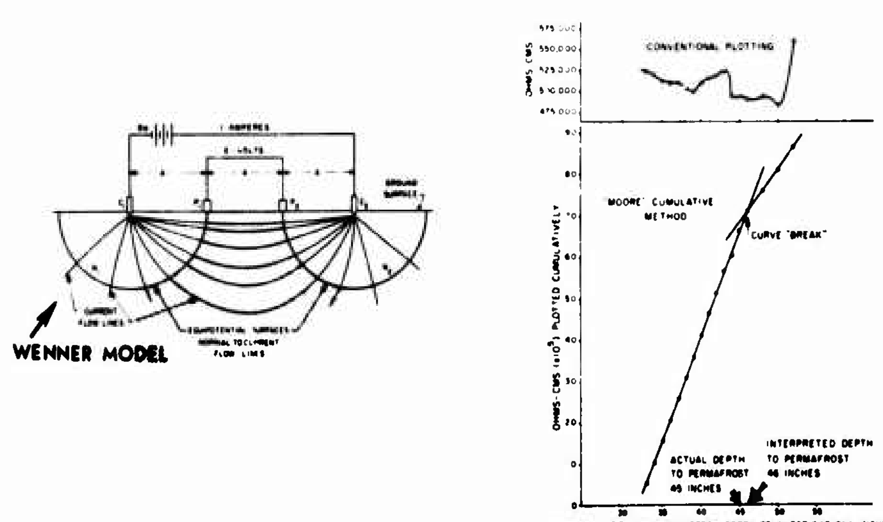


Figure 27. Theory and Instrumentation of Electrical Resistivity

19. DROPPABLE SENSORS

To overcome problems of ground surveys, AFCRL (Molineux, 1955) and WES (1957-1963) developed several devices for airborne determination of soil strength, using projectiles dropped or fired from aircraft. Such an instrument, called an aerial penetrometer, is essentially an aluminum cylinder that looks like a small rocket; it is approximately 2.5 ft long, 2 in. in diameter, and weighs less than 2 lb. The original model was dropped from propeller-driven aircraft and had a spring mechanism to measure the impact. If the penetration resistance is greater than the pre-set level, a flare is released through the hollow barrel and rises to several hundred feet altitude as a visible "go-no-go" indicator. Figure 28 shows an exploded view of this device.

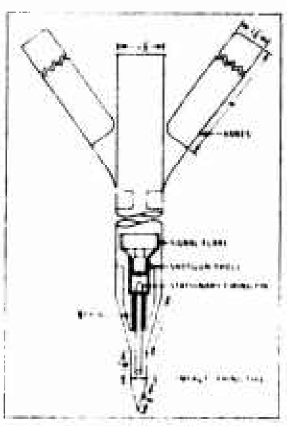


Figure 28. Assembly of Aerial Penetrometer

For tactical reconnaissance missions, an additional development by AFCRL facilitated an improved means of deployment and indication. This penetrometer can be ejected in quantities up to 10 in a pre-selected sequence from tip-tank launchers on jet aircraft at speeds of approximately 450 knots and altitudes of 1000 ft above the terrain. For multiple deployment the firing sequence is 0.5 sec apart, with the penetrometers thus landing about 300 ft apart. Ejection is by an electrically detonated charge contained within the launching system; the penetrometers are inert. They are nearly buried in their own holes, depending on the soil strength encountered, and are expendable. Soil hardness is indicated by the appearance of a self-contained light bulb visible through the vertically impacted cylinder. The launching mechanism shoots the penetrometers downward and backward at a component velocity sufficient to cancel the forward speed of the aircraft, so that the penetrometer hits the ground at 350 ft/sec directly under the spot where ejection takes place.

The penetrometer is aerodynamically stable with pop-out vanes governing its fall, which takes about 1.5 sec from ejection to impact. The strength-indicating mechanism is adjustable to allow determination of soil hardness through a range of values that might be required by various aircraft landing loads.

Development is now underway by AFCRL for another aerial penetrometer, operating on a depth of penetration principle, that is more pertinent to determination of relative strength differences in pre-selected areas. This device consists of two parts whose different weights cause them to separate on impact and transmit their relative displacement by radio telemetry.

The device, cylindrical in shape, has fins at the top to serve as an antenna and to provide aerodynamic stability. The cone-shaped bottom surface consists of the point of the penetrating cone and rod surrounded by a conical ring that is the impact surface of the penetrometer shell. It is about 24 in. long and less than 4 in. in diameter.

Relative displacement is transmitted by successive cutting of electrical wire pickups spaced along the shell length. Each cutting causes an increase in resistance of the circuit modulating the transmitter output, so the frequency of the tone signal increases with each cut. The depth of penetration is indicated by the number of step increases in the signal frequency; the uniformity of deceleration is indicated by their spacing. The signal from each penetrometer can be distinguished by an identifying code from a pre-set grouping of pickups. Figure 29 shows the configuration of this new development.

WES is currently developing and testing an air-dropped oscillator or dielectric penetrometer to penetrate or lie on the surface of the terrain for measurement and telemetry of the dielectric constant and conductivity of soils (USAEWES, 1966c). These parameters can be correlated to soil type and water content.

NASA has also conducted feasibility studies and testing of impact-type devices for determining the hardness of terrestrial surfaces (McCarty et al, 1964).

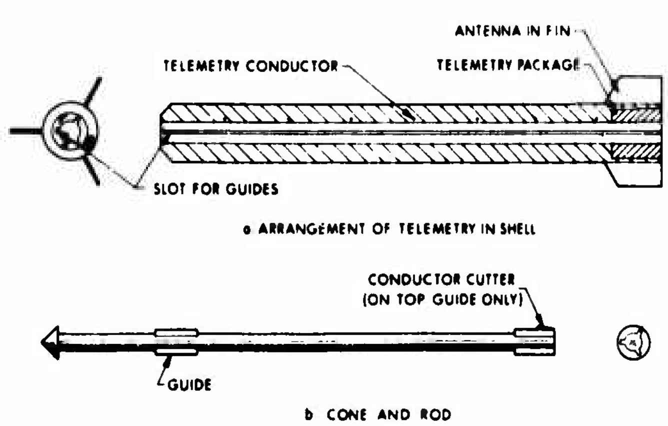


Figure 29. Modified Aerial Penetrometer With Telemetry Capability

20. IMPLANTED OR ROVING SENSORS

Implanted or air-dropped sensors for determining and monitoring meteorological conditions are well-developed and extensively used; the "Grasshopper" weather telemetry station is an example of this type sensor. Counterpart devices for monitoring sea state are in use by the Navy. Similarly, implanted sensors for determining hydrologic data are frequently used by the Army Engineers and the Department of the Interior.

A development effort sponsored by AFCRL at the Army Engineer Waterways Experiment Station resulted in an automated sensing station that can obtain and telemeter data on soil moisture, soil strength, and local weather variables from a remote site to a central headquarters (USAEWES, 1965). Purpose of the system is to provide information on landform conditions that might be affected by seasonal or climatic variations.

Soil moisture can be measured by electrical resistance sensors with a digitized microammeter readout or, preferably, by a neutron soil-moisture meter which would not be sensitive to possible effects of soil chemical composition on its resistance. Soil strength is determined by a hydraulic-loaded penetrometer operating at a constant penetration rate through a 2 ft depth. Obstruction would cause abandonment of the probe cycle and repetition at an adjacent location. The strength data can be recorded at the receiving station as an X-Y plot of force versus depth. Values of wind speed and direction, surface air and soil temperature, and precipitation falling on the site are also obtained and telemetered. The system can be actuated on a pre-programmed basis, on demand, or whenever rainfall occurs signalling a possible change in site properties of concern.

The station can either be permanently implanted or employed on a small track-laying vehicle that is self-propelled by battery power and guided with a cable attached to a central control mast about which the vehicle spirals. Telemetry can be by teletype or by radio link. All measuring sensors are transistorized, with automatic selection by logic circuits in the control unit. The teletype, in addition to paper-printing the data, also stores it on punched paper tape for possible future computer operations. The station and sensing system is capable of unattended operation for long periods of time at remote locations under extremes of temperature conditions. Figure 30 shows this penetrometer/vehicle system.

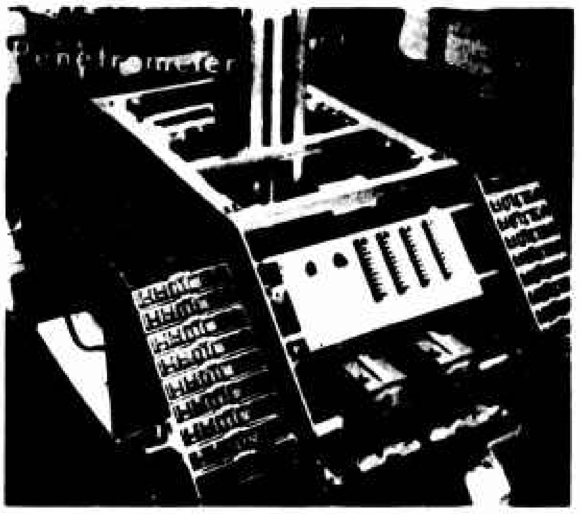


Figure 30. Remote Controlled Roving Ground Penetrometer Monitoring System

21. AIRBORNE SENSING LIMITATIONS

It is recognized that many limitations exist for full employment of types and arrays of airborne sensors. Many of these limitations are caused by the atmosphere intervening between the sensor and the terrain, such as air turbulence, absorption or attenuation of solar radiation by water vapor or ozone, cloud cover and rain, and lack of natural illumination for night photography. However, as the sensing wavelength increases, atmospheric absorption of the available energy generally decreases.

Some restrictions are due to the sensors themselves, including photographic resolution, non-linearity or distortion of camera film, and altitude or slant range limitations. Sensor operation in aircraft also presents problems of temperatures or pressure effects on the equipment, aircraft vibration, and requirements for size, configuration, electric power, and antenna placement. Degradation of photography through non-optical glass is another problem.

Still other limitations to efficient sensing and imagery interpretation are caused by the terrain and its topography. These include vegetation cover, surface scattering, shadowing, and man-made camouflage.

Some or most of these limitations can be overcome by proper design and planning of the sensing systems and operational missions, but they must always be considered.

22. DATA GATHERING VEHICLES

Useful terrain and environmental data can be obtained all the way from the earth's surface outward to space, ranging from sensors implanted below ground to manned or unmanned satellites.

The use of automated surface-based systems telemetering their data to a central headquarters has been well established. The gathering of seismic, gravity, magnetic or electrical data on earth properties by surface measurements is standard practice. Placing sensors on ground-vehicle booms or on platforms, towers, or arches enables obtaining "remote" surface data pertinent to the individual sensing technique.

The sensing vehicle most widely and successfully used is, of course, the aircraft. This vehicle combines the advantages of range, speed, and repetitive coverage with its capacity for containing large weights and volumes of sensing instrumentation and self-power generation. Sensing aircraft have ranged from helicopters and small observation planes through multi-engine reconnaissance aircraft to the supersonic X-15 type from which much photography has been obtained. Many governmental agencies (USGS, AFCRL, U. S. Department of Agriculture, and NASA in particular) have aircraft permanently instrumented and used for terrain property sensing. In addition, many commercial organizations have aircraft devoted to the mission of testing, verifying, and applying remote sensing instrumentation. Also, many universities, especially those conducting sponsored research in the earth sciences, operate well-equipped aircraft for data gathering assignments.

High-altitude balloons offer an intriguing potential for photographic or other sensing of terrain, as they provide a stable, vibration-free, and relatively controlled platform with slower passage over the ground than either aircraft or rockets reaching comparable altitudes.

Much earth photography has been obtained from past sounding rockets such as the Viking and Aerobee, and the Mercury series of satellite flights started a vast library of earth photographs obtained from space. The GEMINI series in particular has provided considerable information on terrain characteristics and mapping.

IV. Applications

I. INTRODUCTION

The success of a military air or ground operation is frequently dependent upon the proper utilization — that is, application — of terrain. The elements and parameters of the terrain that are pertinent to its proper utilization include its dimensions, composition, form, and dynamics. The terrain factor-effect relationships are, of course, not known for all military activities and must be determined by controlled performance testing. The ability to select an alternate terrain is necessary to meet any changing tactical situation or environmental elements.

Relevant military applications pertinent to terrain analysis include: strategic and tactical planning, air and ground navigation, and guidance, geodetic control, and target location; reconnaissance, surveillance, and detection of activities including perimeter intrusion, tunnels, and nuclear tests; intelligence; mapping and charting; site selection of bases, airfields, missile silos, roads, and surface and underground facilities such as command and control centers; location of sources of power and construction materials; aerospace craft and vehicle trafficability; analogous area analysis; design of weapon systems and destruction effects; surface modification and soil stabilization; prediction warning and protective measures against terrain movement and natural catastrophic events (earthquakes, volcanisms, landslides, floodings, tidal waves, and major erosive actions); and inducing actions

to degrade the capability of an enemy by causing landslides, flooding, and the instability of structures by inducing loss of strength in terrain foundations materials.

2. MODEL CRITERIA

Adequate quantitative terrain data incorporated into performance-prediction mathematical models are required for each terrain application. Essential lacking data would then be easily identified for required input to the model (WES, TR3-726, Vol. 1).

When the critical value limits of the terrain fact rs selected for input to the model change, the model must be modified. The data obtained from pilot-performance testing of the activity on terrain determines the critical values that are fed into the model concept.

Performance results are introduced into the analytical model to determine design criteria. These criteria are then translated into factor values representative of global environmental characteristics and are reflected in the design of new equipment and system components.

3. SELECTED TYPES OF APPLICATIONS

The applications described below are typical, since they relate to common operational problems. They are: trafficability, surface modification, analogous areas, and site selection.

3.1 Trafficability

The maneuverability of vehicles and aircraft on natural surfaces is based on the pedologic, geologic, hydrologic, physiographic, climatic, vegetative, and bearing strength properties of the terrain. An evaluation of all these elements of a terrain contributes to the rapid assessment of the conditions that will affect trafficability (U. S. Army WES, 1954, p. 9; U. S. Army WES, 1961, p. 10; AFM 88-51, p. 92; Pressman, et al, 1961; Needleman, 1962).

A terrain is considered trafficable when the forward thrust of a vehicle overcomes the rolling resistance at a specified rate of speed (Burns, 1960, p. 15). Certain soils in a comparatively dry state can be trafficable for many vehicles and aircraft (Womack, 1965).

Predicting the speed of vehicles along a planned route is dependent upon adequate available pertinent factor value data.

3.2 Surface Modification

Most surfaces require some modification for operational use; these modifications can be achieved through mechanical or chemical means. Standard construction procedures and equipment can prepare any surface for use by removing obstacles, substandard soil, vegetation, and rock horizons in the profile, and replacing them with suitable local indigenous materials (Needleman, 1961, p. 38). The properties of a soil may be improved by compaction, moisture control, blending of added materials, and stabilization. In the case of airstrips, the placement of landing mats and plastic membranes over a reinforced soil is widely practiced. A combination of these methods and concrete or asphalt surfacing is the optimum approach to improve a natural surface for a great deal of traffic (AFM 88-52, p. 175; U. S. Army WES, Misc. Paper 3-605, p. 3).

3.3 Analogous Areas

The use of accessible analogous terrain for conducting studies and tests substitutes for the inability to conduct such activities at the scene of anticipated operations. The comparison of similar areas requires the establishment of the factor classes upon which the analogies will be based. Although no area is entirely coincident, it is possible to identify areas that are nearly similar in the majority of the factors. These areas may have had an identical geologic and climatic history influence a similar development of their soil, vegetation, and topographic characteristics, resulting in approximately equal terrain factor values (Van Lopik, and Kolb, 1959, p. 3; Wood and Snell, 1960, p. 15; Curtis, 1966, p. 134).

In a case study of analogous areas in an arctic environment, 46 terrain subfactors were considered for a determination of a suitable military test site.*

Research, development, engineering, and testing on selected sites in the U.S. that are analogous to other world environmental conditions are standard procedure in programs sponsored by Department of Defense agencies. The lack of completely analogous test sites results in some inaccurate performance data, but a range of values can be deduced to indicate the limits of each factor class in the design parameters (Stoertz, 1961, p. 7; Grabau, 1967a, p. 4). Worldwide conditions

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* The factors may be characterized by slope or relief; elevation; vegetation type, density/height, tree trunk diameter; soil profile; rock type, strength, and structure; depth of thaw; depth of frost; depth, thickness, and continuity of permafrost; depth to water table; soil shearing strength; snow cover depth and density; river depth and velocity; stream width and bottom conditions; flooding; seasonal icings; slides and mudflows; earthquakes, volcanic activity; thermal factors (ground temperature, freeze-thaw index, and mean annual temperature); and miscellaneous environmental factors between terrain and climate (duration of darkness, blowing sand and dust, blowing and drifting snow and ice crystals).

are analyzed to develop optimum design criteria and provide a minimum number of limiting conditions for maximum utilization (Van Lopik and Kolb, 1959, p. 11).

3.4 Terrain Studies

So that alternate choices are available in the event of contingency action, the military is conducting continuing terrain studies throughout the world. This is being done so that extensive pre-mission reconnaissance will be minimized.

3.4.1 SITE SELECTION

The investigation of the earth's surface and subsurface for the location of airfields, roads, radar and missile sites, storage depots, and other facilities on all types of terrain (soil, snow, ice, permafrost, coral, laterite, etc.) is essential to successful global operations. The tactical situation in limited wars invariably demands the deployment and operational use of sites with marginal conditions in remote areas (Needleman, 1962, p. 69).

The terrain requirements for a specific mission determine the type of data needed for analysis. Each terrain factor in the model is evaluated for the application. Figure 9 outlines these sequences and shows the approach in arriving at recommended solutions for the decision-maker or commander.

4. APPLIED EARTH AND RELATED SCIENCES

The scientific areas that offer an insight into regions lying above and below the surface of the earth are geology, geodesy, geography, hydrology, glaciology, soil mechanics, soil science, soil engineering, geomagnetism, seismology, oceanography, ecology, biology, and electronics (AFM 88-53, p. 1; Strahler, 1963, p. 1; Strahler, 1960, p. 287; Berkner, 1962, p. 2180).

The data on the parameters peculiar to each application are correlated with data from these interrelated disciplines to draw reasonable conclusions from observed phenomena. Unfortunately, reports are usually issued in the major field of interest, incorporating only the terrain data applicable to that field of interest.

5. TERRAIN ENGINEERING

Engineering history is marked by failures of structures such as dams, bridges, tunnels, reservoirs, highways, and airfield runways due to weak foundation materials, faulty design, or excessive loading on the structure and associated earthwork construction (AFM 88-53, p. 191).

Of the various terrain features that commonly present engineering problems, rivers present the most severe problems. Plains and plateaus, on which most large operations take place, do not present as many severe problems. Hills and mountains are general obstacles and only suitable for small operations (AFM 88-53, p. 146).

Flood control and construction of foundations over permafrost, coral, or laterite present special problems. The construction of underground installations in consolidated and unconsolidated materials necessitates different techniques and equipment (Nat. Acad. of Sci., 1963).

As the effects of climate are more pronounced in an arid, tropical, or arctic environment, compared to a temperate zone, construction in these areas present unique problems.

5.1 Natural Resources for Military Operations

Indigenous construction materials and a useable water supply are essential for successful military applications. Purification of the water may be necessary when pollution, salinity, or minerals are found in the source of supply (AFM 88-53, p. 270).

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V. Research and Development Status

1. INTRODUCTION

The acquisition of subsurface data, particularly by remote methods, is not keeping pace with the requirements for quantitative terrain information (underground sites). Modern ground-test techniques can be used to expeditiously determine the suitability of a terrain, in any environment, for various uses, but airborne techniques have not yet been fully developed for operational use.

Gaps in our knowledge concerning the static and dynamic behavior of natural materials are being studied, and laboratory and field experiments are being conducted to evaluate the theoretical results.

Comparative methods of analyzing terrain parameters of analogous areas and the formulation of rigorous mathematical terrain models of global environments are attaining increased accuracy for operational utility. Key terrain characteristics can be evaluated, but the analysis of microfeatures requires supplementary sources of information from ground data, indirect measuring techniques, photogeologic analysis, and photogrammetric processing. Computer assistance is necessary to permit the rapid interpretation of terrain data and requires the development of programming methods for reducing data to a suitable matrix format (Figure 31).

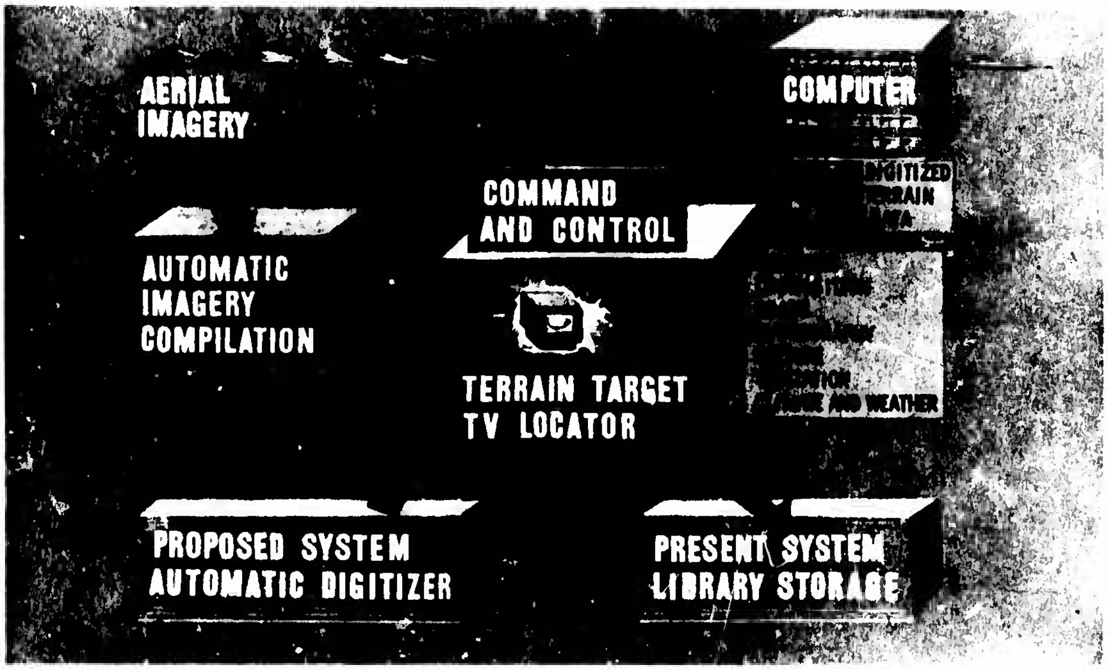

Figure 31. Simulated Terrain Data Processing Approach

Terrain characteristics and the properties of soil, ice, and snow have been intensively studied by the Air Force, Army, and Navy. Terrain in polar, temperate, and desert environments was the major research interest in the past, but present research is concentrating on vegetated surfaces and landforms in a tropical environment, especially on the identification and measurement of the effects of vegetation on military operations and the exploitation of natural terrain.

2. CLASSIFICATION OF THE ENVIRONMENT

Techniques are being developed for classifying geographic areas and their respective subordinate physiographic regions in more quantitative terms, so that their effects on military operations can be evaluated. Such data are the basis for comparing one area with others that are similar in the majority of environmental parameters (Strahler, 1963, p. 326).

The Army's Waterways Experiment Station (WES), Terrestrial Sciences Center (ATSC), and Natick Laboratories (USANL) are improving methods for classifying and correlating the environments with the terrain. Sites in a particular environment are selected in accessible terrain and are representative of other areas

of the world where there is a possibility of future military activity. The terrain factors are analyzed and the resultant data utilized to optimize equipment design (Wood and Snell, 1960, p. 2; Grabau, 1967a, p. 3).

3. TERRAIN RESEARCH

Problems relative to the identification of terrain parameters and instrumentation and methodology for measuring those parameters are being studied by AFCRL, AFWL, ATSC, USANL, USAEWES, and ONR. These organizations are shifting a portion of their concentration from contact to remote sensing techniques for obtaining terrain data.

Data obtained from contact and non-contact methods are correlated and synthesized for application to military activities. As each study produces data for a particular use, an intensive analysis is done from a narrow perspective.

A comprehensive terrain research program of military significance has not been undertaken, although a number of efforts by DoD and their contractors have produced valuable data. These investigations resulted in the development of several terrain classification systems, but some gaps still exist and additional research is warranted. Some of these gaps are presently being studied by many organizations in the following areas.

3.1 Geology

Studies of geologic processes are being made to determine the static and dynamic properties of invididual landforms and materials. This type of information is being applied to problems that include site selection of airfields, stability of underground structures and miscellaneous types of facilities, rapid excavation for the construction of military installations, location of natural hazards and power sources, and crustal studies for the detection of underground objects and communications.

3.2 Geophysics

Research on seismic methods for monitoring the earth's interior is being carried out in an effort to improve our ability to detect underground nuclear explosions. With improvements in seismic techniques and the necessary instrumentation, other tactical applications are possible (Bates, 1962, p. 2207; AFCRL, 1967, p. 280). Detailed gravimetric, magnetic, seismic, and geothermal studies will enable us to predict eruptions of volcanoes, to better understand the mechanisms involved in volcanic eruptions, and to utilize the energy associated with volcanoes, such as geothermal steam (Kiersch, 1964, p. 18).

The determination of site stability by geologic, gravimetric, and seismic methods offers great promise for monitoring earth movements on a continuous basis. With such a monitoring system, precautionary measures could be taken to prevent personal injury and damage to facilities from earthquakes and tsunamis (sea waves) (U. S. Coast and Geodetic Survey, 1964, p. 72).

3.3 Geodesy

Geodetic knowledge from improved ground, airborne, and orbital surveying techniques will redefine the shape of the earth, interrelate all points of the earth for better mapping and navigation accuracies, and refine astronomic and terrestrial constants for inertial guidance and new navigation systems. The areas of increased knowledge will include more accurate data on: undulations of the geodetic ellipsoid network of the earth; deflections of the vertical gravity component; the composition, thickness, warping, and rigidity of the crust, mantle, and the core of the earth; the movements of large land masses; the precise location of the magnetic and geographic poles; and response of crust to tidal accelerations, degree of crustal isostatic equilibrium, oceanic swell and tide cycles; all major gravity anomalies and equipotential surfaces up to satellite altitudes (Williams, 1963, p. 3; AFCRL, 1965, p. 135; AFCRL, 1967, p. 289).

Star catalogues are being refined to more accurately show their positions and motions. Research regarding the precise determination of astronomical constants is being continued. The moon and its precise librations are being studied, and large scale mapping, sufficient for precise reference in space and planetary exploration, is progressing (Williams, 1963, p. 4; Strahler, 1963, p. 71).

3.4 Geomagnetism

Studies of the earth's magnetic field (main field and transient magnetic variations) are continuing. The main field category includes magnetic surveys, magnetic charts, secular changes, rock magnetism, magnetic anomalies, and studies regarding its origin. The transient variations of the lunar, solar, and magnetic field are being investigated to develop more accurate world navigation charts (AFCRL, 1960, p. 10-1).

Correlations of magnetic field measurements from rockets, earth satellites, and space probes with those obtained on the ground is expanding our knowledge of the geomagnetic field and the internal composition and structure of the earth (Strahler, 1963, p. 142).

4. SOIL MECHANICS

Research is directed toward the maximum utilization of soils for military construction purposes.

Efforts are planned to advance the understanding of the static and dynamic characteristics of soils under varied loads. Methods are being developed to predict the profile and engineering properties of soils in order to determine the needs for final site selection and utility. Accompanying these efforts is the search for improved sonic, electrical, electromagnetic, seismic, and radioactive techniques for rapidly measuring soil properties. Soil models and analog techniques are being applied to predict the trafficability of global terrain. Research will be continued on the response of soils and rocks to high-energy impulses (Tsai, 1967, p. 33).

5. REMOTE SENSING

Ultraviolet, polarization, and passive microwave sensing techniques are being studied to provide interpretable imagery of terrain data. (Figure 8).

New applications of existing techniques are being developed, and the instrumentation is continually being improved. Radar scatterometry, multi-spectral photography, and passive microwave thermal imaging are representative areas that have been improved by advanced instrumentation development (USAF Scientific Advisory Board, 1966, p. 12).

Research toward the development of a semi-automated terrain-data-interpretation process has recently been initiated. Pattern recognition, spectral discrimination, and mapping by computer printout of terrain characteristics are potential areas of application needing much further investigation. Advances in fiber optics may enable an automated generation, presentation, and comparison of the terrain data with imagery presently available. The tape recording of sensor outputs permits automated enhancement, storage, and contrast comparisons that far exceed the dynamic range of present photographic film (Van Lopik, 1962, p. 777).

The continued growth and refinement of a data bank of target and background signatures is sorely needed. Such reference information will guide the test, interpretation, and application of new imaging sensors by providing ranges of exposure settings for optimum sensor use. Discrimination of land contours, spatial extent, and spectral reflectance of material composition, using such data bank information, could enhance the detection and interpretation of natural backgrounds and penetrate possible masking or camouflage of targets.

The use of sensors in orbiting platforms is a new technique that is still in its infancy, but the vast potential of space photography has already been demonstrated by NASA. Research directed toward the use of other kinds of sensors in orbiting platforms should now be initiated in order to exploit their potentials. The repeated coverage of wide geographic areas of the earth's surface by orbiting sensors would be of obvious benefit for assessing changing conditions, seasonal, climatic, and otherwise.

6. SCIENCES OF MARINE ENVIRONMENT

Advances in oceanography (studies in marine gravimetric, magnetic, seismic, heat-flow, and the specialized interrelated disciplines of traditional science — geology, chemistry, biology, and physics) are refining theories on the earth's history and internal structure (Strahler, 1963, p. 292).

The potential fields of applications to be derived from studies in ocean technology are aircraft landing sites on floating sea ice, underwater missile sites, underwater storage and tank fields, salt water conversion processes, scientific waste disposal, trans-ocean pipelines, nuclear damage in water areas, predicting and inducing tsunami waves, mineral recovery and extraction, seafood farming, submarine navigation, etc. Methods for preventing beach erosion and harbor and waterways over-sedimentation are being investigated.

7. COMPUTERIZATION OF DATA

Data on terrain factor values will be computerized and used in controlled laboratory experiments, followed by field tests in varied environmental and terrain conditions. The data obtained from these tests will permit rapid analysis for comparison with the established criteria of specific uses (Anstey, 1960, p. 4).

Efforts are being made toward establishing guidelines for acquiring earth-science data that will be amenable to mathematical processing. Past records include errors that will remain until replaced by new data.

As a research aid, computer technology is a much more efficient use of geoscience libraries than the inadequate bibliographic procedures. For many years a need has existed for the automated tabulation of references and scientific data. Many libraries are awaiting the results of present research studies before incorporating such computer methods. The increasing volume and complexity of the scientific literature of military importance indicates the need for continued research in this area to improve data retrieval methods (Pangborn, 1967, p. 18; Miesch, 1967, p. 13).

VI. Conclusions and Recommendations

1. CONCLUSIONS

The success of global military operations is based upon the tactical exploitation of terrain in all environments. As terrain is a common denominator of earth science and the art of warfare, a multi-disciplinary understanding of terrain parameters in quantitative terms is necessary in modern technology. An efficient system of acquiring, quantifying, interpreting, and evaluating such data on a global basis is absolutely essential. The significance of terrain parameters varies with the use, but the instrumentation and methodology to collect the information are similar.

A combination of ground, airborne, and future orbital scientific techniques can be used to develop a "quick-response" type of capability for obtaining ground data and predicting use of terrain for specific military purposes. This capability could be further enhanced by the computerization of geoscience information and the development of methods for retrieving selected data for rapid synthesis and evaluation.

Advanced warfare concepts and recent conflicts have emphasized the inadequacy of our quantitative global terrain data. With our limited data, we are unable to perform certain operations on a routine, efficient, rapid, and automated basis. This problem has been partially solved by the introduction of electronic skills,

but problem areas still exist, particularly obtaining data below the surface of the earth. Scientific and technological gaps are only gradually being identified, delineated, studied, and surmounted by additional research and development, but research funds are limited. The only exception to this austere support occurs in the category of priority programs in narrow fields when requirements are established for special applications. The current state of knowledge is in the form of an incomplete foundation upon which new scientific information must be added from productive research, development, and test efforts.

Military-sponsored applied research has achieved some technologic progress in semi-automated terrain-analysis capabilities, but the progress has been slow and expensive. This approach has involved the use of research performed by private contractors. Certain problems remain to be solved for improved capability.

Microterrain data are not recorded for many parts of the world, and available data are plotted on small-scale maps that are inadequate for conducting all types of military operations. Critical terrain factor values for specific uses are difficult to predict without adequate measured data. This type of precise information currently must be obtained by ground methods of investigation. Remote sensing methods from aircraft and possibly from orbital altitudes could provide the necessary quantitative information, if an optimum terrain investigating system and advanced analytical techniques were developed.

Terrain problems that should be investigated by remote sensing technology are: bearing strength as a function of moisture, climate, vegetation, soil, and related parameters; resolution of microrelief; identification of type and determination of properties of complex soils (laterites, permafrost, coral); location of adequate water supplies; site selection for natural landing areas; detection of clandestine nuclear tests; determination of weapons effects; occurrence of natural catastrophic events above and below the surface (landslides, volcanic eruptions, tsunamis, earthquakes); micromovements; and rock failures in underground structures, affecting weapon system accuracies.

Although conventional aerial photography is presently the most reliable sensor for providing geometrical measurements and locations of terrain features, it is not possible to examine subsurface features directly from any film and filter combinations. Stereoscopic viewing of such photography can reveal much qualitative information on the microfeatures. Photography has a higher resolution of ground characteristics by an order of magnitude greater than current radar or infrared systems flown at comparable altitudes (Neal, 1965).

New films, improvements in photographic resolution and contrast, and techniques for recording spectral information from the near-ultraviolet through the near-infrared are providing methods for identifying terrain characteristics.

At wavelengths longer than 0.9 μ, imaging on film is not presently possible. Various infrared, radar, and microwave line scanners can supplement photography to generate imagery interpretable in terms of terrain properties. Parameters such as surface planes of weakness (jointing, faulting, fracturing), lateral variations in soil moisture and ground water, and soil or rock types are susceptible to identification and discrimination from such imagery. To date, this interpretation is not reliable, but research and development regarding the origin and distortion of images with time, weather, aspect angle, or polarization will reduce the ambiguities in the interpretation.

The interpretation of remote sensor records has not kept pace with the development of the individual sensors. Development of the capability to correlate terrain properties with the characteristics of images or the electromagnetic energy levels received is progressing. The premise that each material has characteristic signatures at differing wavelengths, varying with the physical state of the material, is accepted in the scientific community. Identification of the materials and their engineering properties through diagnostic spectral characteristics analysis, supported by a minimum of valid and reliable "ground truth" data for correlation, will achieve a milestone in terrain-analysis technology.

With further research and development in computerized techniques, remote sensing will enable an economical compilation of the engineering properties of terrain for any area susceptible to overflight.

The development of an automated terrain-data-gathering and efficient display system cannot be achieved without adequate support to perform the basic and applied research needed for a modern level of competence.

The report has stressed the importance of the quality of terrain input data, the adequacy of an evaluation model, and the appropriateness of performance data in research, development, testing, and engineering. The recommendations listed below are designed to pinpoint those areas requiring more intensive investigation to alleviate the gaps in the advancement of terrain-analysis technology. Such objectives can be attained only by having complete knowledge of the pertinent terrain parameters and factor values. In the cases where data are lacking, an efficient and rapid information acquisition system is essential for an improved military capability.

2. RECOMMENDATIONS

2.1 Future work should develop an integrated method for describing the surface configuration of landscape patterns and correlating them with airborne sensor data.

2.2 Further study should be made regarding: the type of terrain data that can be derived from imagery for photogrammetric use, he correlation of "in situ" terrain characteristics with sensor imagery obtained from an airborne or orbital system.

2.3 A major effort should be directed toward quantifying terrain parameters for computer storage, retrieval, reduction, and data analysis in digital or analog form (Beckett, 1962; Wood and Snell, 1960, p. 11).

2.4 Work should continue on the development of a classification system for all types of terrain, water bodies, and hazards. The data should be in matrix format and applicable for varied military uses and for the conductance of analogous area studies (Beckett and Webster, 1965).

2.5 Assemble an atlas of indexed representative global landform and microrelief features with accompanying air and ground photos, other related imagery, and large-scale topographic, geologic, vegetation, and soil maps (Bredahl and Kiefer, 1957; Kiefer, 1957). Expand and update the "USAF Index to Aerial and Ground Photographic Features Throughout the World," dated 30 September 1946, Supplement No. 1, 2 January 1949, including newly discovered variations of landforms.

2.6 Continue performance tests of aircraft and ground vehicles on controlled natural surfaces to produce factor values for military mobility on natural terrain (Johnson, 1962; Tsai, 1967; Air Force Flight Test Center, 1963).

2.7 Implement a program for measuring, under controlled experimental conditions in the laboratory and field, the spectral reflectance properties of all types of earth materials, to determine atmospheric and visibility parameters influencing the reflectance measurements.

2.8 Continue the growth and refinement of a "target-signature" data storage repository (bank) containing data on the reflectance properties of specific terrain materials needed for the interpretation of sensor imagery obtained from laboratory, field, and airborne or spaceborne sensor platforms.

2.9 Continue efforts to develop automated methods for pattern recognition, spectral or spatial discrimination, image contrast enhancement, computer print-out of mapped imagery, and digital format for storage of sensor data.

2.10 Test the various sensors at balloon, rocketborne vehicle, and satellite altitudes to establish their capabilities and/or limitations.

2.11 Apply the available techniques of terrain analysis to siting of all major military installations, to provide the maximum engineering data, efficiency, and economic benefits.

3. SUMMARY OF KEY CONCLUSIONS AND RECOMMENDATIONS

3.1 Conclusions

Terrain is a common denominator of earth science and art of warfare.

Global terrain data are incomplete or lacking.

Ground and airborne data-acquisition techniques are available.

Orbital techniques are experimental.

Present and potential applications are numerous.

Remote sensing offers much promise in earth science research and development.

3.2 Recommendations

Develop better criteria for terrain evaluation.

Refine methods of measuring microterrain features and critical factor values.

Develop sensors with improved resolution for interpretation of microterrain factors.

Develop orbital methods of high resolution terrain sensing and data telemetry.

Develop automated methods of data storage, retrieval, processing, reduction, interpretation, and handling.

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FM 30-21	Aerial Photography, Military Applications
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FM 31-71	Operations in the Arctic
FM 70-10	Mountain Operations
FM 72-20	Jungle Warfare
FM 101-10	Staff Officers Field Manual
AFM 1-2	USAF Basic Doctrine
AFM 1-4	Air Doctrine, Air Defense Operations

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AFM 200-50	Photographic Interpretation Handbook
AFM 400-5	Logistical and Operational Planning Manual, USAF

3.2 Air Force Systems Command Manuals

AFSCM 80-1	HIAD	Handbook of Instructions for Aircraft Design
AFSCM 80-6	HIAGED	Handbook of Instructions for Aerospace Ground Equipment Design
AFSCM 80-8	HIMD	Handbook of Instructions for Missile Design, (Missile and Space Technical Facilities)

AFSCM 80-9	HIASD I	Handbook of Instructions for Aerospace Systems Design (General Design Criteria)
AFSCM 80-9	HIASD V	Handbook of Instructions for Aerospace Systems Design (Environmental Engineering)
AFSCM 80-14		Design Criteria Handbooks

3.3 Air Force Regulations

AFR 0-2	Numerical Index of Standard Air Force Publications
AFR 0-6	Subject Index of Air Force Publications
AFR 80-2	Documents Used in the Management of Air Force R & D
AFR 80-14	Testing/Evaluation of Systems, Subsystems, and Equipment
AFR 85-5	Operation and Maintenance of Installation Facilities
AFR 88-15	Engineering Manuals and Guide Specifications for Military Construction
AFR 91-23	Maintenance and Improvement of Grounds

3.4 Air Force Specification Bulletins

106	General Environmental Criteria for Guided Missile Weapons Systems
115	Environmental Criteria for Ground Support Equipment

3.5 Technical Manuals

TM 3-414	Trafficability of Snow
TM 5-230	Topographic Drafting
TM 5-231	Mapping Functions of the Corps of Engineers
TM 5-233	Construction Surveying
TM 5-234	Topographic Surveying
TM 5-235	Special Surveys
TM 5-236	Surveying Tables and Graphs
TM 5-240	Aerial Photography
TM 5-246	Interpretation of Aerial Photographs
TM 5-248	Foreign Maps
TM 5-250	Roads and Airfields
TM 5-252	Use of Road and Airfield Construction Equipment
TM 5-255	Aviation Engineers Manual
TM 5-280	Construction in the Theater of Operations

TM 5-295	Military Water Supply and Purification
TM 5-296	Ground Water Supply for Military Operations
TM 5-297	Well - Drilling
TM 5-302	Construction in the Theater of Operations
TM 5-310	Military Protective Construction
TM 5-330	Planning, Site Selection and Design of Roads, Airfields, and Heliports in the Theater of Operations
TM 5-335	Drainage Structures, Subgrades, and Base Courses
TM 5-349	Arctic Construction
TM 5-350	Military Pipeline Systems
TM 5-366	Planning and Design for Rapid Airfield Construction in the Theater of Operations
TM 5-560	Arctic Construction
TM 5-624	Roads, Runways, and Miscellaneous Pavements, Repairs, and Utilities
TM 5-630	Grounds, Maintenance, Dust and Erosion Control, Repairs and Utilities
TM 5-742	Concrete and Masonry
TM 30-245	Photographic Interpretation Handbook
TM 30-246	Tactical Interpretation of Air - Photos

3.6 Technical Bulletins

TB 5-255-3	Construction of Runways, Roads, and Buildings on Permanently Frozen Ground
TB 5-550-1	Soils Trafficability

Glossary of Terms in Common Usage*

Acceleration of Gravity - The acceleration of a body falling freely in a vacuum due to the gravitational attraction of the earth. The International Committee of Weights and Measures has adopted as a standard or accepted value of 980.665 cm./sec^2 or 32.174 ft/sec^2, but its true value varies with latitude, altitude, and the nature of the underlying rocks.

Active Layer - Annually thawed layer; layer of ground above the permafrost which thaws in the summer and freezes in the winter.

Adobe - An impure, calcerous clay widely used in the United States for making sun-dried bricks.

Age - Any great period of time in the history of the earth or the material universe marked by special phases of physical conditions or organic development; formal geologic time unit corresponding to a stage; informal geologic time unit corresponding to any stratigraphic unit.

Aggradation - The process of building up a surface by deposition; the growth of a permafrost area.

Aggregated - To bring together; to collect or unite into a mass; composed of a mixture of substances, separable by mechanical means; the mineral material such as sand, gravel, shells, slag, or broken stone, or combination thereof, with which cement or bituminous material is mixed to form a mortar or concrete.

Airborne Scintillation Counter - Any scintillation counter especially designed to measure the ambient radioactivity from an aircraft in flight.

Albedo - The percentage of the incoming radiation that is reflected by a natural surface such as the ground, ice, snow, or water.

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*American Geological Institute (1960)

Alkali Flat - A level lakelike plain formed in low depressions where accumulated water evaporates depositing fine sediment and dissolved minerals which form a hard surface if mechanical sediments prevail or a crumbly powdered surface if efflorescent salts are abundant.

Alluvium - A general term for all detrital deposits resulting from the operations of modern rivers, thus including the sediments laid down in river beds, flood plains, lakes, fans at the foot of mountain slopes, and estuaries.

Angle of Repose - The maximum slope or angle at which a material such as soil or loose rock remains stable. When exceeded, mass movement by slipping as well as by water erosion may be expected.

Angstrom Unit - A unit of length of 10^{-8} cm., commonly used in crystallography.

Archipelago - Any sea or broad sheet of water interspersed with many islands or with a group of islands; also a group of islands.

Arid Climate - A climate in which the rainfall is insufficient to support vegetation.

Arroyo - The channel of an ephemeral or intermittent stream, usually with vertical banks of unconsolidated material 2 ft or more high.

Artèsian Water - Ground water that is under sufficient pressure to rise above the level at which it is encountered by a well, but which does not necessarily rise to or above the surface of the ground.

Atmosphere - The gaseous envelope surrounding the earth; the atmosphere is odorless, colorless, tasteless, very mobile, flowing readily under even a slight pressure gradient; elastic, compressible, capable of unlimited expansion, a poor conductor of heat, but able to transmit vibrations with considerable velocity.

Atoll - A ringlike "coral" island or islands encircling or nearly encircling a lagoon. An atoll reef is a ring-shaped, coral reef, often carrying low sand islands, enclosing a body of water.

Avalanche - A large mass of snow or ice, sometimes accompanied by other material, moving rapidly down a mountain slope.

Backshore - Upper shore zone beyond the reach of ordinary waves and tides; one or more nearly horizontal surfaces called berms formed landward from the beach crest; may slope inland.

Badlands - A region nearly devoid of vegetation where erosion, instead of carving hills and valleys of the ordinary type, has cut the land into an intricate maze of narrow ravines and sharp crests and pinnacles. Travel across such a region is almost impossible; extremely rough topography formed in an advanced stage of gullying in poorly consolidated sediments and characterized by sharp-edge ridges separated by narrow and steep gullies.

Bajada - A nearly flat surface of a continuous apron consisting of confluent alluvial fans that make up the general slope in a basin; a series of confluent alluvial fans along the base of a mountain range.

Bar - A mass of sand, gravel or alluvium deposited on the bed of a stream, sea, or lake or at the mouth of a stream forming an obstruction to water navigation.

Barchan - A dune having crescentic ground plan, with the convex side facing the wind; the profile is assymetric, with the gentler slope on the convex side, and the steeper slope on the concave or leeward side; the barchan type is most characteristic of the inland desert regions.

Base Level - The level below which a land surface cannot be reduced by running water. Sea level is considered the principal base level. Principal streams serve as local or temporary base levels for their tributaries.

Basin - A region in which the strata or layers of rock dip in all directions towards a central point such as an inverted dome; a river basin is the total area drained by the river and its tributaries; a lake basin is the basin filled by water of the lake; any hollow or trough in the earth's crust whether filled by water or not.

Beach Berm - Nearly horizontal bench or narrow terrace formed by wave action in unconsolidated material on the backshore of a beach with surface rising behind it and sloping off in front.

Bedrock - The solid rock beneath the loose material, or soil and subsoil, with which most of the land surface of the earth is covered. It is sometimes several hundred feet beneath the surface, but it usually is found at a much smaller depth; in places, especially on steep slopes, it has no soil cover at all.

Bench Mark - In surveying, a mark, usually cut in stone as a relatively permanent material object, natural or artificial, bearing a marked point whose elevation above or below an adopted datum (such as sea level) is known.

Block Diagram - Three-dimensional perspective representation of geologic or topographic features showing a surface area and generally two vertical cross sections.

Bluff - Any high headland or bank presenting a precipitous front; it is usually applied to the slopes bordering a river; these bluffs often formed by the action of the river in cutting into the valley sides.

Bog - An area of soft, wet, spongy ground, consisting chiefly of decayed or decaying moss and other vegetable matter. It often forms in shallow, stagnant lakes or ponds, and is largely produced by sphagnum moss; the latter spreads out from the shores, floating on the surface, and gives a deposit of vegetable matter or peat on the bottom. A swamp or tract of wet land, covered in many cases with peat.

Bolson - A basin; a depression or valley having no outlet; a wide valley drained by a stream flowing through canyons at each end.

Caldera - A large basin-shaped volcanic depression, more or less circular or cirquelike in form, the diameter of which is many times greater than that of the included volcanic vent or vents, no matter what the steepness of the walls or form of the floor. Three major types: explosion, collapse, erosion.

Caliche - Secondary calcerous material occuring in a layer or layers at or near the surface. May be a soft or hard horizon of lime accumulation in the soil, but more commonly the term refers to a cemented layer a few inches to many feet in thickness containing impurities of clay, sand, or gravel. Most caliche deposits appear to form by a variety of processes whereby soil moisture evaporates or deposits its content of calcium carbonate.

Canyon - A gorge, relatively narrow but of considerable size, bounded by steep slopes.

Cave - A hollow space developed in a portion of the earth's crust. A sea-cave may be produced by the action of the waves and also by boulders and pebbles being thrown against a cliff by the sea. It may also be formed by the contraction and expansion of the air in a rock fissure as the waves advance and retreat. Inland caves are often formed in a limestone region where water containing carbon dioxide dissolves out underground channels and enlarges them in places to form caves, usually with a stream flowing through them.

Chain - A mountain system consisting of a collection of more or less parallel ranges, and possibly including plateaus, provided that the general longitudinal arrangement is maintained.

Chemical Weathering - The weathering of rock by chemical processes such as oxidation, carbonation, hydration, and solution.

Climatology - The science that treats of the various climates of the earth and their influence on the natural environment.

Coastal Plain - A plain that borders the sea coast and extends from the sea to the nearest elevated land. It is sometimes formed through deundation by the sea, the beach being later raised by earth movement to form a plain, frequently known as a Raised Beach, or by deposition of solid matter at their mouths by rivers.

Compaction - The increase in density of a soil mass by rolling, tamping, vibrating, or other methods; expressed as pounds of wet soil or dry soil per cubic foot.

Coniferous Forest - A forest of evergreen coniferous or cone-bearing trees carrying needle-shaped leaves. From such forests is obtained the valuable softwood timber of commerce.

Continental Drift - The supposed horizontal displacement of portions of the original continent that comprised the entire land mass of the world to form the present-day continents. It is described as Wegener's Hypothesis.

Continental Shelf - The terrace-like submerged surface bordering the continents, sloping gently and extending as far as 600 miles out under the sea.

Coral Reef - A chain of rocks lying at or near the surface of the sea and built up principally from immense numbers of skeletal marine creatures; both on and behind the reef, fragments of shells, coral, and coral sand are piled up by the wind and wave action, and new land is thus formed. Three more or less distinct kinds of coral reef are recognized: fringing reefs, barrier reefs, and atolls.

Crater - A steep-sided pit or basin, usually at the summit of a volcano, and formed when the top of the volcano was removed by explosion or collapse.

Crevasse - A deep, vertical crack in a glacier. Tranverse crevasses develop across a glacier wherever there is a marked steepening of the slope of its' floor. Longitudinal crevasses, roughly parallel to the direction of flowage, are formed whenever ice is obliged to spread out. Marginal crevasses point upstream from the sides of the glacier.

Deciduous Forest - A forest consisting of trees that lose their leaves at some season of the year. In the case of the monsoon forests, such as those of India and Burma, the trees shed their leaves during the hot season in order to protect themselves against excessive loss of moisture by evaporation. From the deciduous forests is obtained much of the valuable hardwood timber of commerce; the monsoon forests yield such extremely hard wood as teak, oak, elm, and beech from the cool intermediate forests.

Degradation - A process that tends to wear down the land surface; it is usually applied to a river and it involves the deepening of its valley by the river.

Delta - An alluvial deposit formed at the mouth of a flowing stream emptying into the relatively quiet water of a lake, sea, or ocean.

Dendritic Drainage - A tree-like arrangement of a main stream and successively smaller tributaries joining it at acute angles.

Deposition - The laying down in a new location of material that has been carried from another place.

Desert - An almost barren track of land in which the precipitation is so scanty or spasmodic that it will not adequately support vegetation.

Diastrophism - Deformation of the earth's crust by folding, bending, warping, or faulting.

Dome - A curved stratum of rock in which the slope is in all its directions away from a central point.

Drumlin - An elongated, half-egg-shaped hill made up of material deposited beneath glacial ice; it occurs in a previously glaciated region, the long axis lying parallel to the direction of flow of the ice, with the thick, steep end to the north.

Dune - An accumulation, as a hill or ridge, of windblown sand common from erosion in deserts. The sand particles are carried along by the wind and piled into a heap that gradually increases in size until it becomes a small hill; the dune is often commenced where an obstacle of some kind impedes the free movement of the wind. The sand is then heaped against the obstacle until it is covered. By the action of the wind, the shape and size of the dune are always changing.

Dust - Solid matter consisting of minute particles, smaller than sand particles, and occuring everywhere in the atmosphere; it is often carried immense distances by the wind, and is constantly being deposited on the earth's surface. The sources of dust are various: in and near to industrial areas, the smoke from factory and domestic chimneys charges the atmosphere with particles of carbon and other substances; in the deserts dust is raised from the ground by the wind while volcanic dust enters the air during an eruption.

Earth - The fifth in size of the eight major planets in the solar system, and the third in nearest distance from the sun. The solid outer crust of the earth, known as the lithosphere, is partially covered (72%) by an extensive area of water, known as the hydrosphere, and around the earth is a gaseous envelope known as the atmosphere. Although the earth is often regarded as being a sphere, it is actually an oblate spheroid, being slightly flattened at the poles; the polar distance is about 27 miles shorter than the equatorial diameter, that being 7,926 miles in length.

Earthquake - A movement or tremor of the earth's crust that originates naturally and below the surface, it sometimes causes a permanent change of level at the surface, but often the damage done by the shaking provides the only lasting visible effect. It may be produced by a volcanic explosion; earthquakes are common in most volcanic areas and often precede or accompany eruptions.

Ecology - The science that treats of organisms in relation to their environment; it is frequently subdivided into human ecology, plant ecology, animal ecology, and bio-ecology. Bio-ecology deals with the inter-relationships between animal life and plant life. Ecology lies on the frontiers of many areas including geography.

Equatorial Forest - (Tropical Rain Forest) The hot, wet, evergreen forest of the equatorial region, where rainfall is very heavy and where there is no dry season; it extends in parts into the typical monsoon areas. Because of the extreme heat and moisture, the growth is dense and luxuriant.

Erosion - The wearing away of the land surface by various natural agencies, the most important being those consisting of water — the sea, rivers, and rain. Ice, in the form of glaciers, frost, and melting snow also assists in the process of erosion.

Esker - A long narrow sinuous ridge composed chiefly of irregularly stratified sand and gravel. It was once the bed of a stream flowing beneath or in the ice of a glacier, and was left behind when the ice melted.

Estuary - A broad, shallow indentation of a coastline where the sea advances far up a river valley, inundating lowlands and permitting tidal currents to back up the river for some distance upstream.

Exfoliation - A weathering process that consists in the peeling off of thin layers of rock from the surface. In hot deserts it is caused by the heating of the rocks by day and their cooling by night, leading to alternate expansion and contraction. The corners of rock masses especially are broken off, and the surfaces assume a rounded form. The process is often assisted by others, such as the chemical weathering of the outer layers. The term "onion weathering" is sometimes used for exfoliation.

Fault - A fracture of the earth's crust along which movement has taken place.

Fauna - The animal life of a region or of a geological period, corresponding to the term "flora" for plant life.

Firn - Old snow that has lasted through at least one summer; the flakes have changed to grains of spherical shape that may or may not be bonded together. Firn may later become glacial ice.

Fjord - A long, narrow, deep, and steep-sided indentation of the sea along a mountainous coast, covering a sunken valley that was formed by glacial erosion.

Flood Plain - A broad expanse of land in a stream valley that was built up by the deposition of alluvium or sediment carried down by the river during the overflow of water.

Flora - The plant life of a region or of a geological period.

Frost Action - The weathering process caused by repeated cycles of freezing and thawing.

Geodesy - The science of the measurement of the size and shape of the earth and the surveying of large portions of the earth's surface.

Geography - The subject that describes the earth's surface – its physical features, climates, products, peoples, and their distribution.

Geoid - A term used to signify the shape of the earth, an oblate spheroid with certain variations.

Geology - The science of the composition, structure, and history of the earth. It includes the study of the materials of which the earth is made, the forces that act upon these materials and the resulting structures, the distribution of the rocks of the earth's crust, and the history, not only of the earth itself, but also of the plants and animals that inhabited it throughout the different ages.

Geomorphology - The study of the physical features of the earth, the arrangement and form of the earth's crust, and of the relationship between these physical features and the underlying geological structures.

Geophysics - The study of the physical processes relating to the structure of the earth, including not only the lithosphere but also the hydrosphere and the atmosphere. It signifies the physics of the earth linking the sciences of physics and geology.

Glacier - An accumulation of ice that has become so large that sufficient pressure is created to cause movement along the outer margins of the mass.

Gorge - A valley that is more than usually deep and narrow, with steep walls; there is no sharp distinction between a gorge and a canyon. The sides of a small gorge are sometimes nearly vertical.

Grasslands - Those regions of the world where the natural vegetation consists of grass; the rainfall is too light to permit forest growth, but is less scanty and irregular than that of the deserts; the grasslands are thus normally situated between the forest belts and the arid regions.

Gravel - A deposit of rounded stones, usually mixed with finer material such as sand or clay, formed by the action of moving water — by a river or a lake, or by the sea.

Ground Water - Water that has seeped below the earth's surface and occupies porous spaces in the underlying materials.

Ground Water Table - The top of the saturated zone in which ground water has completely filled the openings between individual soil and rock particles. Most of the ground water occurs within a few hundred feet of the earth's surface.

Gulch - A narrow deep ravine with steep sides formed by a torrent.

Gully - A long, narrow channel worn out by the action of the water, particularly in a hillside; it is smaller than a ravine or a valley. The term is often used of a channel produced in the erosion of soil; such a gully normally carries water only during or immediately after rain or the melting of snow.

Hardpan - A hardened or cemented layer of soil, impervious to drainage, lying below the surface.

Hot Spring - A stream of hot water issuing from the ground, often after being heated by buried lava, and commonly occurring in a volcanic region when eruptions have ceased.

Humus - Semidecayed plant and animal matter in soil.

Hydrologic Cycle - The giant circulatory system in which water passes through several stages: from water vapor to precipitation to surface water, and again to water vapor by means of evaporation and transpiration.

Hydrology - The study of water, especially in relation to its occurrence in streams, lakes, wells and as snow and including its discovery, uses, control, and conservation; the science that relates to the water of the earth.

Ice Age - A geological period in which ice sheets and glaciers covered large areas of the continents, reaching the sea in places and lowering the temperature of the oceans.

Ice Field - A uniform, unbroken ice-floe of great extent; a continuous sheet of ice formed when lumps of ice join up.

Ice Floe - An extensive mass of floating ice, detached from the main polar ice, whose limits of dimension are normally within sight.

Ice Sheet (Ice-Cap) - A vast mass of ice and snow that covers large land areas in the polar regions; its surface is almost flat.

Impermeable Rocks - Rocks that, being nearly non-porous, do not allow water to soak into them. This rock may be pervious owing to joints and fissures.

Impervious Rocks - Rocks that do not allow water to pass through them freely; they may be porous.

Insolation - The heat or radiant energy received from the sun by the earth and other planets.

Isostasy - The state of equilibrium existing between the highlands and the lowlands of the earth, due to the fact that the former are made of lighter rock materials than the latter.

Joint - A crack in a mass of rock that has been formed along a plane of weakness.

Kame - A mound of stratified gravel and sand that was formed by the deposition of the sediment from a stream as it ran from beneath a glacier.

Karst Region - A limestone region in which most or all of the drainage is by underground channels, the surface being dry and barren. It is characterized by sink holes and uneven topography caused by the unequal dissolution of porous underlying limestone rock.

Lacustrine - Relating to a lake or lake materials.

Landslide - The downward movement of a large mass of earth or rocks from a mountain or cliff. It is often caused by rainwater soaking into the soil and material on a steep slope; their weight is much increased, and they become more mobile. It may be caused by an earthquake or on the seacoast by the undermining action of the sea.

Lava - Molten rock that flows from fractures in the earth's outer crust out upon the earth's surface.

Leaching - The process by which water percolating downward in the soil, or moving across the surface of the soil, chemically removes soluble minerals from one place and deposits them elsewhere.

Local Relief - Amount of relief within an area in contrast to absolute altitudes above sea level.

Loess - An accumulation of fine sand transported and deposited by the wind.

Magma - Molten material that moves through the rocks of the earth's outer shell and hardens before it reaches the atmosphere.

Mantle Rock - The unconsolidated weathered material that has accumulated on the surface of the earth.

Marl - A mixture of clay and calcium carbonate, although the term is loosely applied to a wide variety of rocks and soils. Some of the marls are marine deposits while others are of fresh-water origin.

Mechanical Weathering - The weathering of rock by physical forces without chemical change.

Mesa - A flat, table-like mass, that slopes steeply on all sides. The harder top layers of rock have resisted deundation, and, being practically horizontal, have maintained a uniform surface parallel to the stratification

Metamorphic Rock - Any rock affected by action of pressure, heat, and water, resulting in a more compact and highly crystalline condition.

Meteorology - The science that investigates the weather, in particular the physical processes that occur in the atmosphere, and the connected processes of the lithosphere and hydrosphere.

Mineral - A natural inorganic substance with fairly definite chemical composition and with distinctive physical characteristics such as crystal form, hardness, color, luster, and type of fracture.

Moraine - An irregularly shaped hill, or ridges and depressions formed by glacial deposition.

Mountain - A land mass reaching comparatively high altitude and having most of its surface in slope and of greater altitude than its surroundings.

Muskeg - A swamp or bog in an undrained or poorly drained area of alluvium or glacial till, or, more especially, in a rocky basin filled with water-saturated muck, decayed vegetal matter, and sphagnum moss incapable of sustaining much weight. The surface is commonly hummocky.

Oceanography - The study of the oceans, including the nature of the water, its movements, its temperature, its depth, the ocean bed, and the flora and fauna.

Outcrop - The portion of a rock stratum that projects above the earth's surface and is thus exposed to view.

Outwash Plain - A level area formed by deposits of minerals carried beyond the ice front of a melting glacier by running water.

Pack-Ice - Large blocks of ice, of greater extent and depth than ice-floes, that were formed on the surface of the sea when the ice-field was broken up by winds and waves, and have drifted from their original position. They are termed "close pack" if the blocks are mainly in contact, "open pack" if they are not. Most of the pack ice gradually melts and disappears in warm weather.

Pedalfer - One of the two types into which soils are sometimes classified; it is roughly equivalent to "soil of a humid region", and is rich in iron and clay. The pedalfers are divided into podzolic and lateritic soils.

Pedology - The science of the study of soils.

Peneplain - A rolling area that has experienced a long period of erosion during which mountains were generally worn down to form relatively flat terrain.

Permafrost - A thickness of soil, superficial deposit, or bedrock of variable depths beneath the surface of the earth in which below-freezing temperature has existed continuously for a long time. The term also used is perennially frozen ground. Permafrost results solely from below-freezing temperature, irrespective of the texture, degree of compaction, water content or lithologic character of the frozen materials involved.

Petrology - The study of the composition, structure, and history of the rocks forming the lithosphere or earth's crust and their mineral structure.

Physiography - The study of the physical features of the earth, their causes and their relation to one another.

Plain - An area of low relief.

Plasticity - The property of a material that enables it to undergo permanent deformation without appreciable volume change or elastic rebound, and without rupture.

Plateau - An area of relatively level land having a higher elevation than a plain and occasionally interrupted by deep valleys and areas of steep slope.

Playa - A dry-lake bed; a track of land that is temporarily filled with water and becomes a shallow muddy lake, but dries up again in hot weather.

Pleistocene - The latest epoch in the geological time scale that includes all of post-pliocene time. It is sometimes called the Ice Age.

Podzol - A type of soil that is characteristic of regions having a sub-polar climate and in a coniferous forest.

Precipitation - Water in solid or liquid form falling from the atmosphere to the earth as a result of the excessive cooling of large amounts of air.

Profile - (Soil) A section through the soil showing the different horizons, or layers, usually designated by the letters A, B, or C, that extend downwards from the surface to the parent material.

Radiation - The process by which a body emits radiant energy in the form of heat. It causes a loss of heat as cooling. Radiant energy is constantly emitted in all directions by the sun, some of this reaching the earth and converted into heat. The earth is constantly losing heat into space by radiation.

Raised Beach - A beach that has been raised by earth movement to form a narrow coastal plain; it is often bounded by inland cliffs.

Recessional Moraine - A deposit of glacial drift laid down during the retreat of a glacier.

Reef - A ridge of rocks, lying near the surface of the sea, that may be visible at low tide but is usually covered by the water.

Rift Valley - A valley lying between two relatively parallel faults.

River Terrace - A platform of land formed beside a river flowing across a plain.

Rock - One of the solid materials of which the earth's crust is mainly composed, being made of an aggregate of minerals. The many different kinds of rocks in the earth's crust are divided into three major classes: igneous, sedimentary, and metamorphic.

Salt Lake - A lake, situated usually in an arid region, in which the evaporation exceeds the amount of water entering through precipitation and inflow, so that the water becomes extremely salty.

Sand - A mass of minute particles of mineral debris that is finer than gravel but coarser than silt. It is also not as fine as dust and is not normally lifted by the winds far above the earth's surface. Its movement is controlled by obstacles in its path and it is often heaped up in mounds called dunes.

Savanna - The tropical region that borders the equatorial forest in each hemisphere and lies between the latter and the hot deserts; the natural vegetation is mainly grass with scattered trees, for there are distinct wet and dry seasons, and the lack of rainfall during the latter prevents the growth of forests except in particularly moist places.

Scarp - A relatively steep, straight slope of any height.

Scrub - A dense mass of low-growing evergreen plants, about 4 to 6 feet high, with occasional taller trees. It is usually found in regions that have insufficient rainfall or poor soil for forest growth.

Seismic Focus - The place below the earth's surface where an earthquake originates and from which the vibrations spread in all directions; it is usually several miles beneath the surface.

Seismology - The science of the study of earthquakes.

Silt - A deposit that is laid down in a river or lake, and is finer than sand but coarser than clay.

Sink Hole - A depression in the earth's surface where water has seeped down and dissolved underlying rocks or collapsed the roofs of caves.

Soil - Unconsolidated material on the earth's surface.

Soil Horizon - A distinctive layer of soil parallel to the earth's surface and having particular chemical and physical properties.

Soil Series - A group of soils having similar profiles except for the texture of the surface soil, and developed from a particular type of parent material.

Soil Structure - The arrangement of soil particles within the soil mass.

Soil Type - A term used in the classification of soils. It is the principal unit used in soil mapping as well as other soil studies.

Steppe - Short grass-type vegetation found on the humid margins of the desert regions.

Stratum - A more or less distinct layer of rock, occurring as one of a series of strata in the earth's crust. Rock strata vary in thickness from a fraction of an inch to several feet, and normally are horizontal.

Striation - A groove made by a glacier indicating the direction of the glacial movement.

Subsoil - The layer of rock particles lying below the true soil; it has less organic matter than the latter. It is less fertile than the true soil, but is penetrated to some depth by the roots of trees and plants.

Swamp - A tract of low-lying land that is saturated with moisture and usually overgrown with vegetation; it differs from a marsh in that it is not ordinarily covered with water, and from a bog in that the latter consists largely of decaying vegetation.

Talus - An accumulated heap of rock fragments derived from and lying at the base of a cliff or very steep mountain slope. The fragments may be large or small and the aggregate heap usually has a form determined by gravity and angle of rest of the material involved.

Tectonic Force - A force originating within the earth's interior, resulting from the expansion, contraction, or the transfer of molten matter, involving both the deformation of the earth's crust and the movement of molten material from one place to another.

Terminal Moraine - A deposit of glacial drift marking the farthest advance of a glacier.

Topography - A detailed description or representation of the features, both natural and artificial, of an area, that are shown on topographic maps.

Trellis Drainage - The pattern formed when major streams are arranged in relatively straight parallel lines with tributaries joining them at right angles.

Tsunami - A huge sea wave occasionally experienced along the coasts of Japan and other regions in the Pacific Ocean, caused by an earthquake taking place on the ocean bed; the wave rises to progressively greater heights as it approaches the coastline, and on a single occasion has been known to cause the deaths by drowning of thousands of people.

Tundra - A broad area of grasses, bushes, mosses, and stunted trees lying between subarctic forests and polar seas.

Valley - A long narrow depression in the earth's surface with a regular downward slope.

Volcanic Ash - Fine particles of lava that have been ejected from a volcano in eruption. The particles are coarser than those of volcanic dust.

Volcanism - The transfer of igneous or molten matter that is frequently accompanied, preceded, or followed by earth movement.

Water Table - The surface of the ground water or the surface below which the pores of a rock are saturated with water. This surface is uneven and it is also variable.

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Appendix A

Terrain Programs in Department of Defense

1. AIR FORCE

Investigations by the Air Force Cambridge Research Laboratories (OAR) in the use of natural terrain for military operations began with studies of seismic propagation through sea ice in 1950. This led to long-term glaciological studies of ice shelves and their suitability as landing strips for aircraft (Assur, 1956; USAF AFM 86-5 Ice Airfields, 1958) Engineering studies of sea ice were culminated in Operation ICE WAY in 1961, which verified the capability of sea ice to support flight operations of the heaviest of Air Force aircraft.

A 5-year program of photogeologic identification of terrain in all environments, field investigations, site evaluations, development of techniques, and proof tests of ice-free natural land areas in Greenland was completed in 1960. This program provided detailed scientific descriptions of a number of natural soil surfaces in arctic areas that could support flight operations.

Based on these proven techniques for assessing terrain and selecting airstrip sites for use in their natural unimproved or semi-prepared condition, similar studies of dry lake bed (playa) landforms were undertaken in 1961. These involved considerations of location, bearing strength, surface roughness, seasonal conditions, site monitoring for degree of useability, site stability, and morphology.

Concurrent studies of natural terrain concerned the quantification of terrain parameters, research in the remote sensing of terrain by airborne methods, and evaluation of analogous areas. Geophysical measurements were made of typical geologic regions involving seismic, magnetic, gravimetric, and electrical resistivity measurements of surface and sub-surface structures.

Research pertaining to the landforms of global humid and tropical regions included photogeologic interpretation and analogous area studies. Field and airborne investigations of natural geothermal sources throughout the world were undertaken, primarily in Iceland and Italy.

The playa and remote sensing programs were extended to the arid regions of the world. These areas are in the Middle East, Near East, South America, and Australia.

Other agencies participating in Air Force programs have been the Army Engineers, Army Natick Laboratories, Naval Civil Engineering Laboratories, Naval Oceanographic Office, and U. S. Geological Survey. Universities and commercial organizations provided much laboratory and field assistance.

The Air Force Weapons Laboratory (AFSC) began their terrain and civil engineering research studies in 1960 to: study the effects of weapons on different soil and rock structures, develop the technology of base facilities, select sites on varied types of terrain to support facilities, and develop soil-stabilization techniques. The agency conducts studies in the evaluation of engineering properties of terrain by geophysical and remote sensing methods. Site selection studies were expanded in 1964 to include the location of suitable natural landing strips in support of operations for all types of aircraft in the Air Force inventory.

The Air Force Flight Dynamics Laboratory has been designing aircraft landing gears suitable for operating on natural or stabilized terrain and on asphalt, cement, or concrete runways. The parameters incorporated into the designs are surface roughness, bearing strength, dimensions of runways, and flight zones, wheel loading, tire size, and other related factors for all AF aircraft.

The Air Force Flight Test Center (AFSC) conducts performance tests of all aircraft on varied types of runways to determine operational characteristics and criteria for maximum capabilities and limitations. Modifications to the prototype models are made dependent upon the test results.

The Hq USAF, Directorate of Civil Engineering (AFOCE) has been responsible for the administration of the civil engineering forces and the assignment of specific operational problems for resolution to the field commands. These problems pertaining to terrain include soil stabilization, selection of sites for permanent or expedient airstrips for contingency operations, and repair or emergency construction of facilities.

The Air Force Civil Engineer Construction Operations Group (CECOG), established in 1966, is the field extension of the Hq USAF Directorate of Civil Engineering (AFOCE) as an operating subordinate unit to AFOCE. CECOG is responsible for the field organization, training, deployment, use, and logistical support of the special engineering forces to meet the requirements of the Air Force global mission. One of their major functions is the use of site selection teams for rapidly locating contingency airfields and other facilities on natural terrain to meet the expanding operational needs of the strategic, tactical, defense, and limited war forces.

2. ARMY

Corps of Engineer studies of terrain properties and vehicle mobility were initiated in the early 1930's at the Ohio River Division Laboratories and at the Waterways Experiment Station at Vicksburg, Miss. Soil trafficability studies were expanded by the Ordnance Department in 1942 and concentrated at the Waterways Experiment Station in 1945. Corollary efforts were in soil stabilization, vehicle trafficability, and aircraft landing mat research, development, and evaluation.

The Snow, Ice, and Permafrost Research Establishment was organized in 1949 to investigate the properties of polar terrain and problems of construction in an extremely cold environment. This group was combined in 1961 with the Arctic Construction and Frost Effects Laboratory (established in 1953) to form the Cold Regions Research and Engineering Laboratory (CRREL), redesignated as Terrestrial Science Center (TSC) in 1968. The Transportation Corps similarly studied operations in a polar environment, conducting vehicle and light aircraft (fixed wing and helicopter) trafficability programs since 1950.

Other Army agencies conducting theoretical and experimental investigations of terrain properties by ground and airborne methods are the Engineer Research and Development Laboratories (renamed Army Mobility Equipment Research and Development Center in 1964) and the Geodesy Intelligence and Mapping Research and Development Agency (renamed Engineer Topographic Laboratories in 1967). The Land Locomotion Laboratory at the Army Tank-Automotive Command (renamed as a Center) develops the criteria for the design of ground vehicles and conducts terrain-vehicle interaction studies for cross-country mobility. The Army Natick Laboratories was established in 1953 to develop methods for protecting military personnel and equipment in all global and regional environments. The USANL also has been responsible for climatological studies of terrain, the development

of criteria for analogous area methods, and efficient logistical use of supplies and equipment in support of military operations. Most of the efforts of the Army agencies are under the jurisdiction of the Hq U. S. Army Research Office, Corps of Engineers, and the Army Materiel Command.

3. NAVY

Terrain studies by the Navy began when the U. S. Navy Amphibious and Training Base established a beach trafficability unit in 1945 to investigate the use of beaches in operations. In 1950, the Navy delegated the responsibility of beach trafficability in DOD to the Army Engineer Waterways Experiment Station.

The Office of Naval Research performed studies of global terrain and its classification since 1950. It also initiated the long-term study of remote sensing of the environment, including terrain properties, that is mainly devoted to terrain quantification and earth science applications.

The Naval Civil Engineering Research and Evaluation Laboratory was organized in 1950 as a research unit of the Construction Battalion Corps under the Bureau of Yards and Docks. It has been concerned with installations, construction, ship-to-shore transportation, equipment, materials, and methods that are related to the engineering properties of terrain. The organization was later redesignated as Naval Civil Engineering Laboratory.

The Naval Ordnance Laboratory conducts studies of water and ice properties related to underwater ordnance and weapons. The Navy Electronics Laboratory has performed considerable work on ice properties and devised extensive instrumentation for surface and subsurface operations in a polar environment. The Naval Oceanographic Office is engaged in intensive investigations of ice surfaces, coastal shelves, reefs, barriers, marine science, sea water parameters, and submarine terrain in addition to major oceanographic studies.

Appendix B

Classification of Terrain Data

I. INTRODUCTION

The majority of terrain studies and classifications are usually qualitative or a description of the genetic origin of various landform features. A quantitative approach defines terrain parameters by a series of numerical values that offer the advantage of achieving accuracy in mapping. This approach also permits the computerization of data on all terrain parameters for an efficient determination of the effects of either an individual factor or a group of selected factors on a particular activity (see Figure 31 in report).

A semi-quantitative system combining the genetic approach with the digitization of the terrain factor values avoids over complexity yet provides more objectivity than the qualitative method in characterizing the terrain for its military significance. The terrain factor subunits of any geographic region can be identified by a series of designated digits or matrixes. Additional digits indicating any preferred range of values can be added to a matrix grouping for supplementary definition as necessary.

2. TERRAIN AND SOIL CLASSIFICATION SYSTEMS

2.1 Terrain Classification

Most terrain classification systems are qualitative and, therefore, not designed to evaluate terrain for a specific use. These qualitative systems merely describe in prose all the elements of the terrain environment, necessitating ground surveying for planning tactical operations.

2.1.1 PHYSICAL GEOGRAPHIC SYSTEM

In military geography, the regions of the world are described by the predominant physical elements of land-surface forms, as shown in Figure B-1. The major descriptive units are plains, plateaus, hills, and mountains.

2.1.2 GEOMORPHIC SYSTEM

This approach provides a genetic method for interpreting the geological structure and changing climatic processes and weathering action resulting in differential erosion of varying resistant lithology and geomorphic evolution of the landscape. The major units of classification are mountains, terraces, beaches, mesas, glacial features, etc., as listed in Table B-1.

2.1.3 REGIONAL PHYSIOGRAPHIC TERRAIN ENVIRONMENT

This method combines the physical geographic and geomorphic systems, subdividing large regions into smaller areas and predominant landform units. The terrain is classified by a synthesis of data on the geology and its processes, rocks, and stratigraphic formations, soils, vegetation, and the climate. The concept is largely intuitive, statistical, and indirect, but it can result in reliable data when employed by skilled scientifically trained analysts (Curtis, 1966).

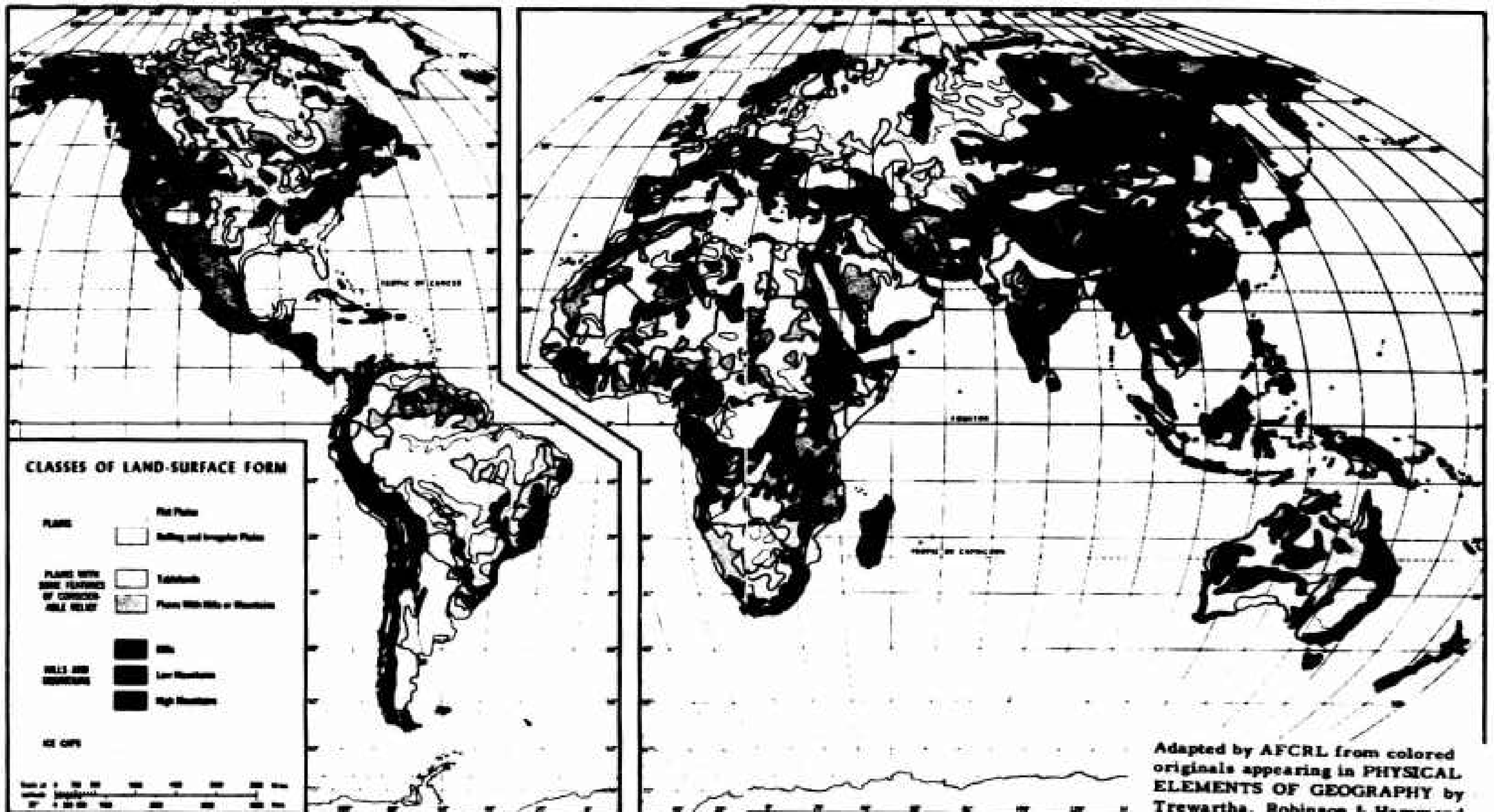
Figure B-2 shows the extent of glaciation over a large portion of the world (Flint, 1961, p. 53), and Figures B-3 through B-8 illustrate the distribution of the other key terrain elements.

2.2 Classification of Rocks

Rock classifications are shown in Table B-2, Table B-3, and Table B-4. Generalized rock properties are listed in Table B-5.

2.2.1 CLASSIFICATION OF IGNEOUS ROCKS

In Table B-3, igneous rocks of similar chemical composition or mineral content are listed in the vertical columns; those of similar textures are listed in the horizontal columns. Classification of each variety is dependent on both texture and chemical composition.



Adapted by AFCRL from colored originals appearing in PHYSICAL ELEMENTS OF GEOGRAPHY by Trewartha, Robinson & Hammond, 5th Ed. 1967. McGraw-Hill Book Co.

Figure B-1. Land Surface Forms (World Distribution)

Table B-1. Summary of Landform Types, Material, and Use

Landform	Materials	Use
Waterlaid		
Flood Plains	Fine-grained and well-stratified interbedded fine silts, sand, and gravel.	Highway, airfield construction; large structures require pilings.
Filled Valleys	Coarse sands and gravels to fine silts and clays	Highways, airfield construction; drainage structure required.
Continental Alluvial Plains	Thin silt cover underlain by stratified semi-consolidated materials of all textures	Highways, airfield, and building construction; drainage for dam sites required to prevent leakage.
Alluvial Fans and Related Forms		Highways, airfield, and building construction; drainage structure required; water supply.
Talus Cones	Rock fragments	
Alluvial Cones	Medium size rock fragments	
Alluvial Fans	Silt, clays, sand, gravel	
Delta Fan	Silt, clays, sand, gravel	
	Unconsolidated sands and small gravel with pockets of silt and clay	
Deltas	Silt, clays, sand, and gravel in stratified, cross-bedded, thick deposits of unconsolidated deposits	Source of construction materials.
Dry Lakebeds (Playas)	Unconsolidated fine sands, clays, silts, and salts	Roads, airfields, and buildings; foundation support for structures required.
Beach Ridges	Sand and gravel	Road, railroad lines; source of construction material.
Coastal Plains	Interbedded clays, silts, and sands in unconsolidated deposits	Road, railroad lines on undissected areas; landslide conditions; drainage controls required.
Tidal Flats	Silt, clay, and sand	Roads require stabilization; source of construction materials.
Marsh and Swamp	Peat, muck, silt	Temporary roads must be stabilized.

Table B-1. Summary of Landform Types, Material, and Use (Cont'd)

Landform	Materials	Use
Glacial		
Eskers	Sand, gravel, and sand	Roads, railroad lines; source of construction material.
Kames	Fine sand, silt, and gravel	Source of construction material.
Outwash Plains	Stratified sand and gravel	Source of construction material and foundations with stabilization.
Terraces	Sand, gravel, clays, silt	Foundations for structures require stabilization; source of construction materials.
Lakebeds		Foundations for structures require stabilization; drainage controls needed.
Delta Deposits	Coarse sand and gravel	
Near-Shore Deposits	Coarse silt and sand	
Deep-Water Deposits	Silts and clays	
Till Plains	Silt, clay, gravel	Foundation for structures require stabilization; drainage controls needed.
Moraines	Silt, clay, sand, boulders	Source of construction material; drainage controls needed; foundation for structures require stabilization.
Drumlins	Sand, clay, and gravel	Source of construction material.
Windlaid		
Sand Dunes	Sand	Source of sand for construction; foundation for structures requires stabilization.
Loess	Silt	Foundation for structures requires stabilization.

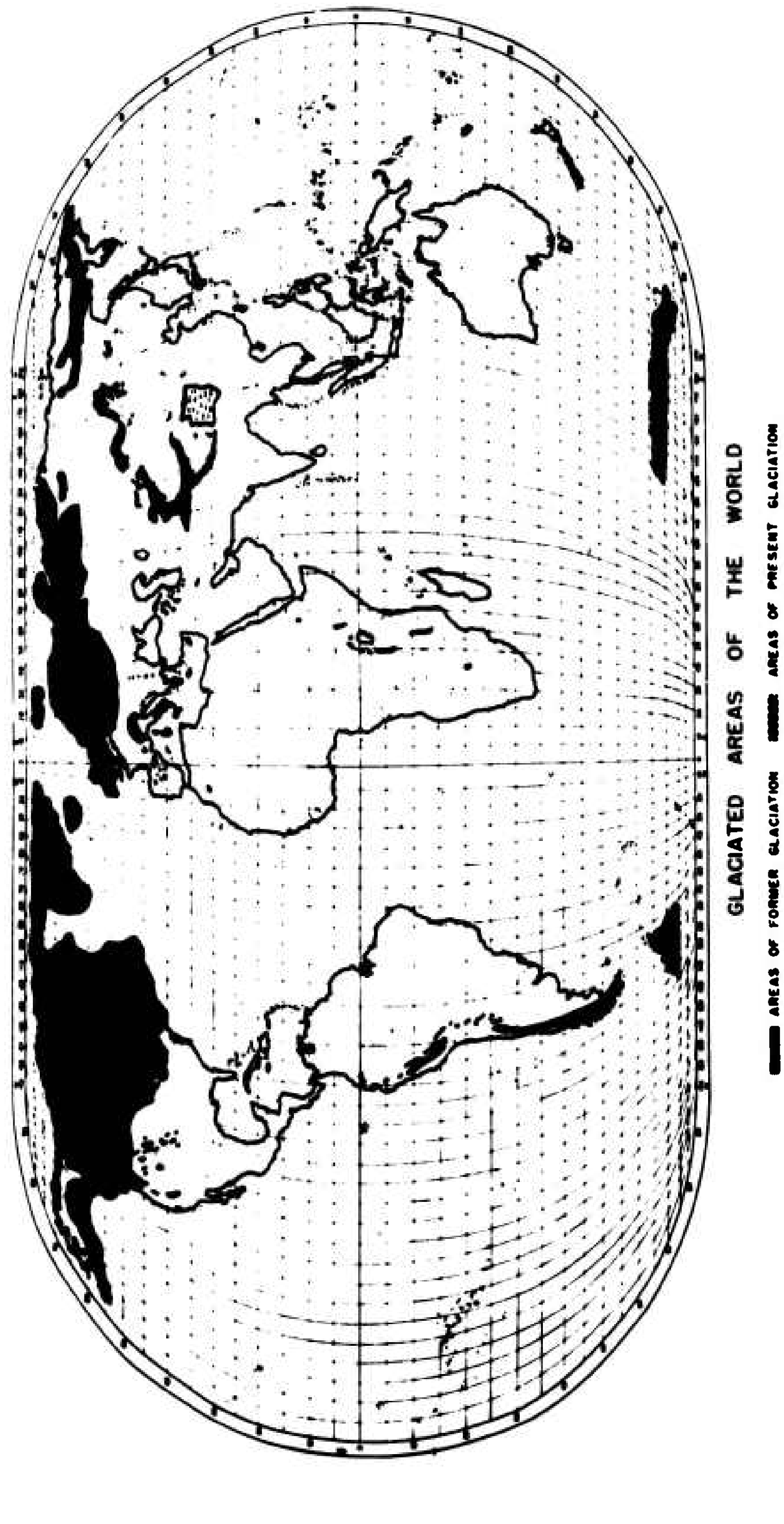


Figure B-2. Glaciated Areas (World Distribution)

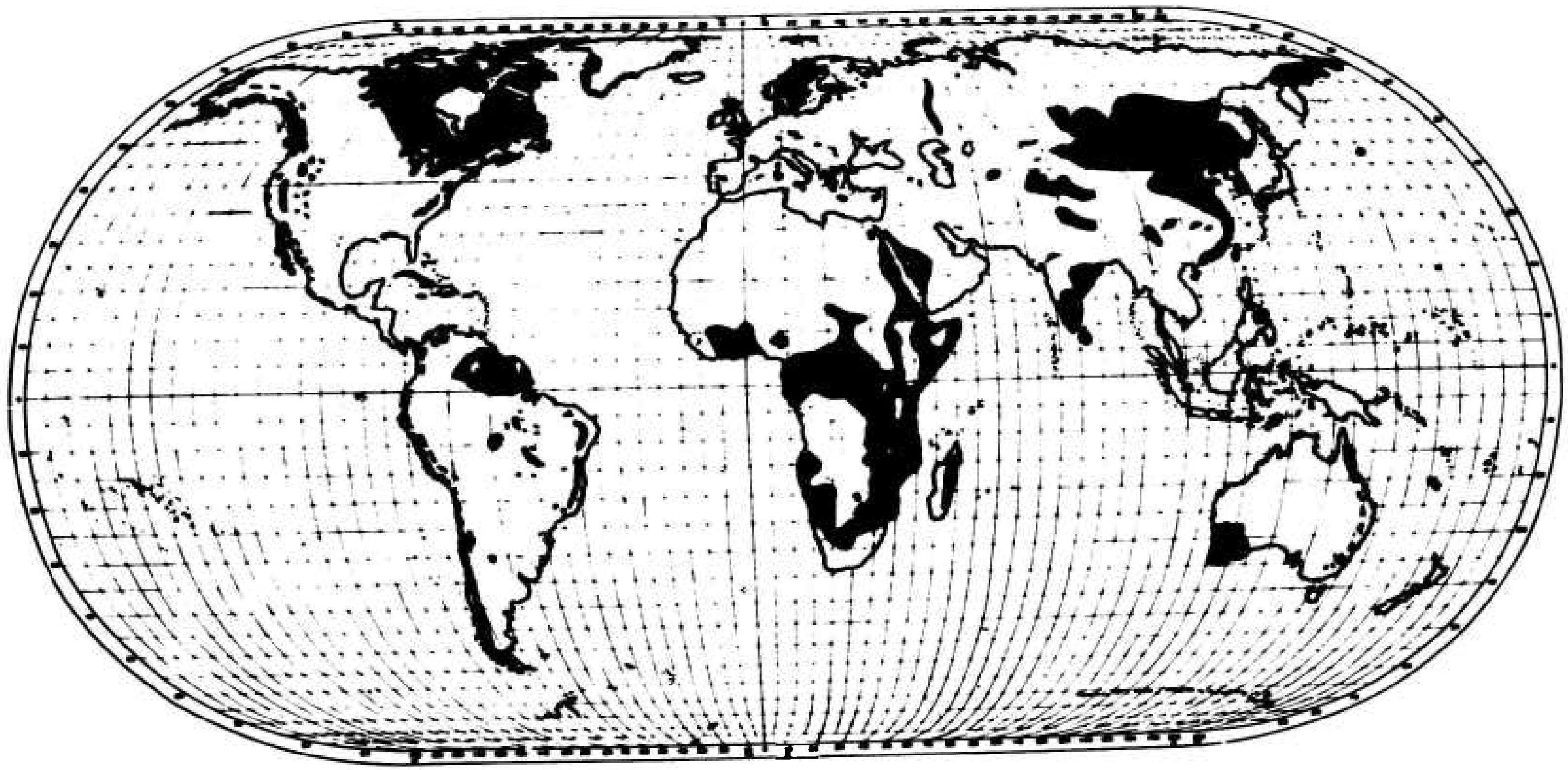


Figure B-3a. Igneous Rocks (Intrusive) (World Distribution)

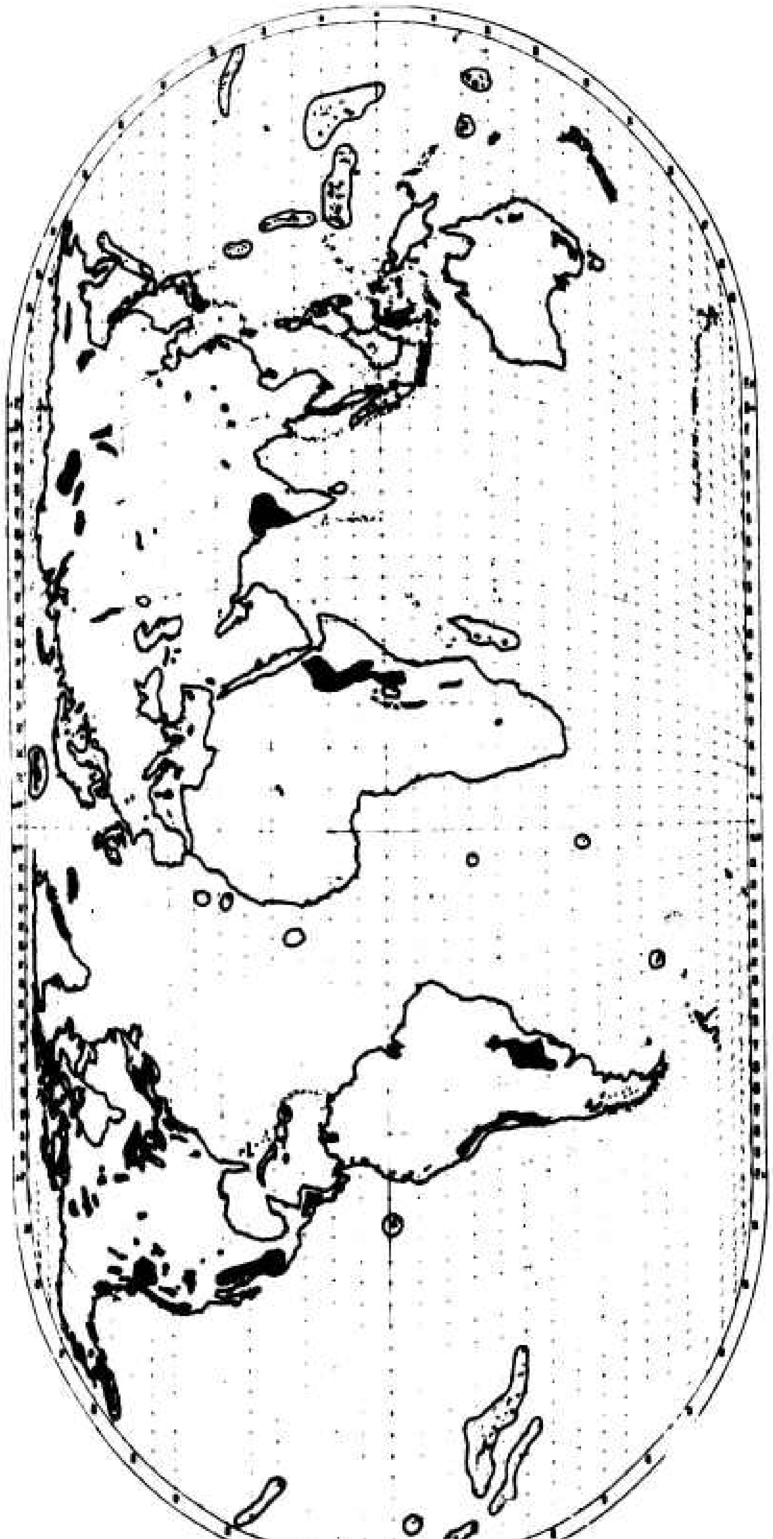


Figure B-3b. Igneous Rocks (Extrusive) (World Distribution)

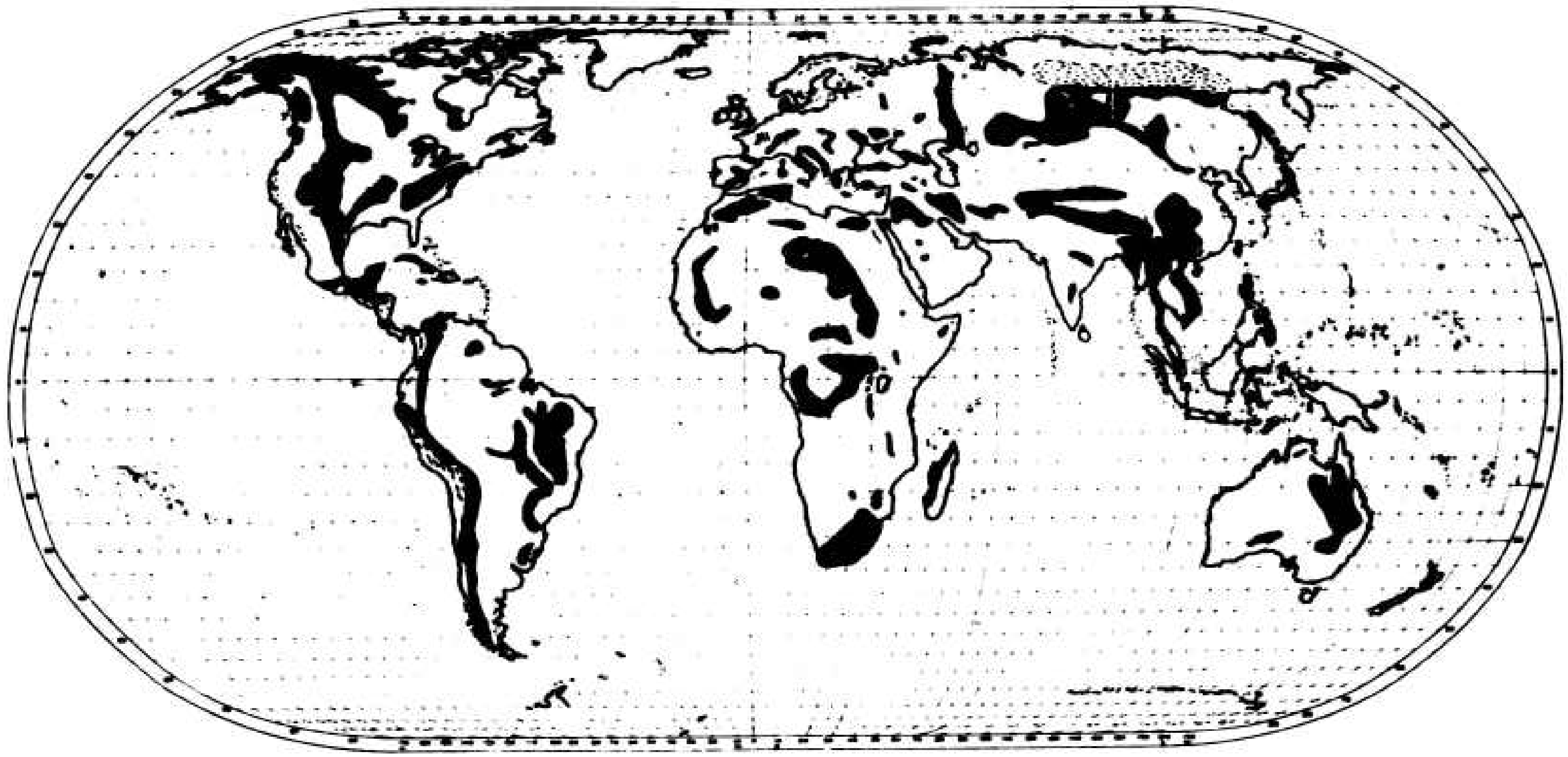


Figure B-4. Sedimentary Rocks (World Distribution)

Figure B-5. Metamorphic Rocks (World Distribution)

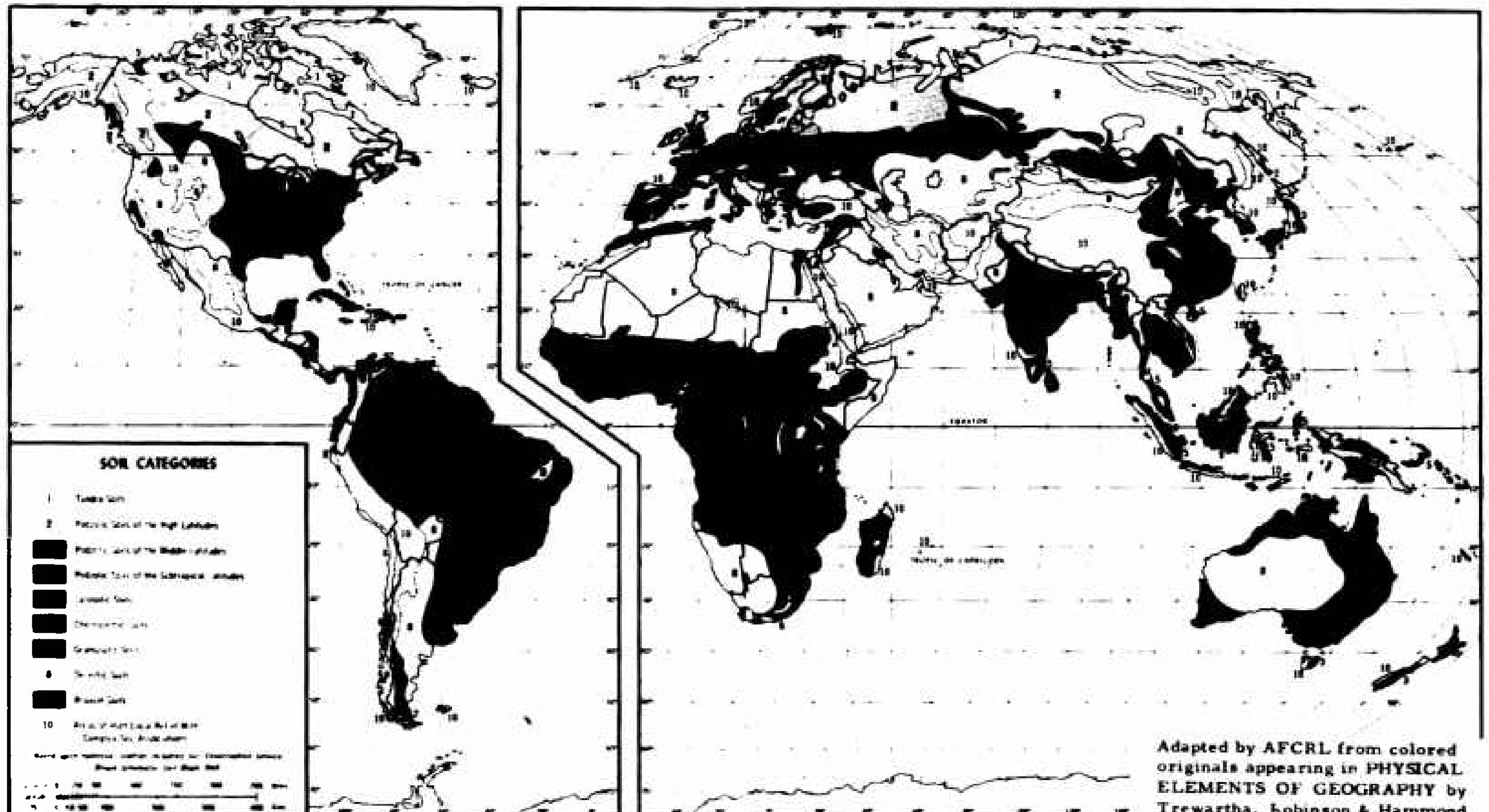


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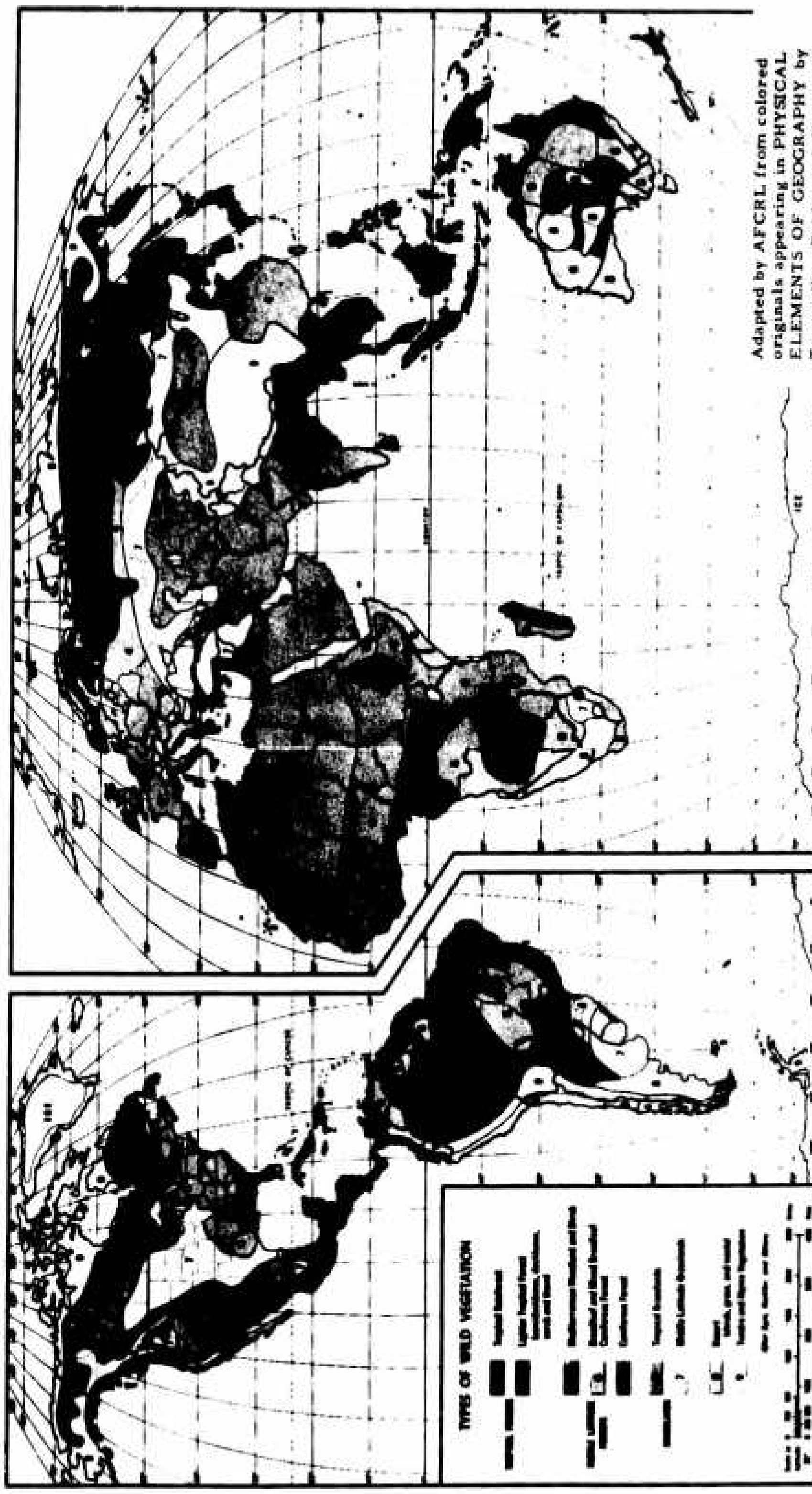
Figure B-6. Soil (World Distribution)



Adapted by AFCRL from colored originals appearing in PHYSICAL ELEMENTS OF GEOGRAPHY by Trewartha, Robinson & Hammond, h Ed. 1967, McGraw-Hill Book Co.

Figure B-7. Vegetation (World Distribution)

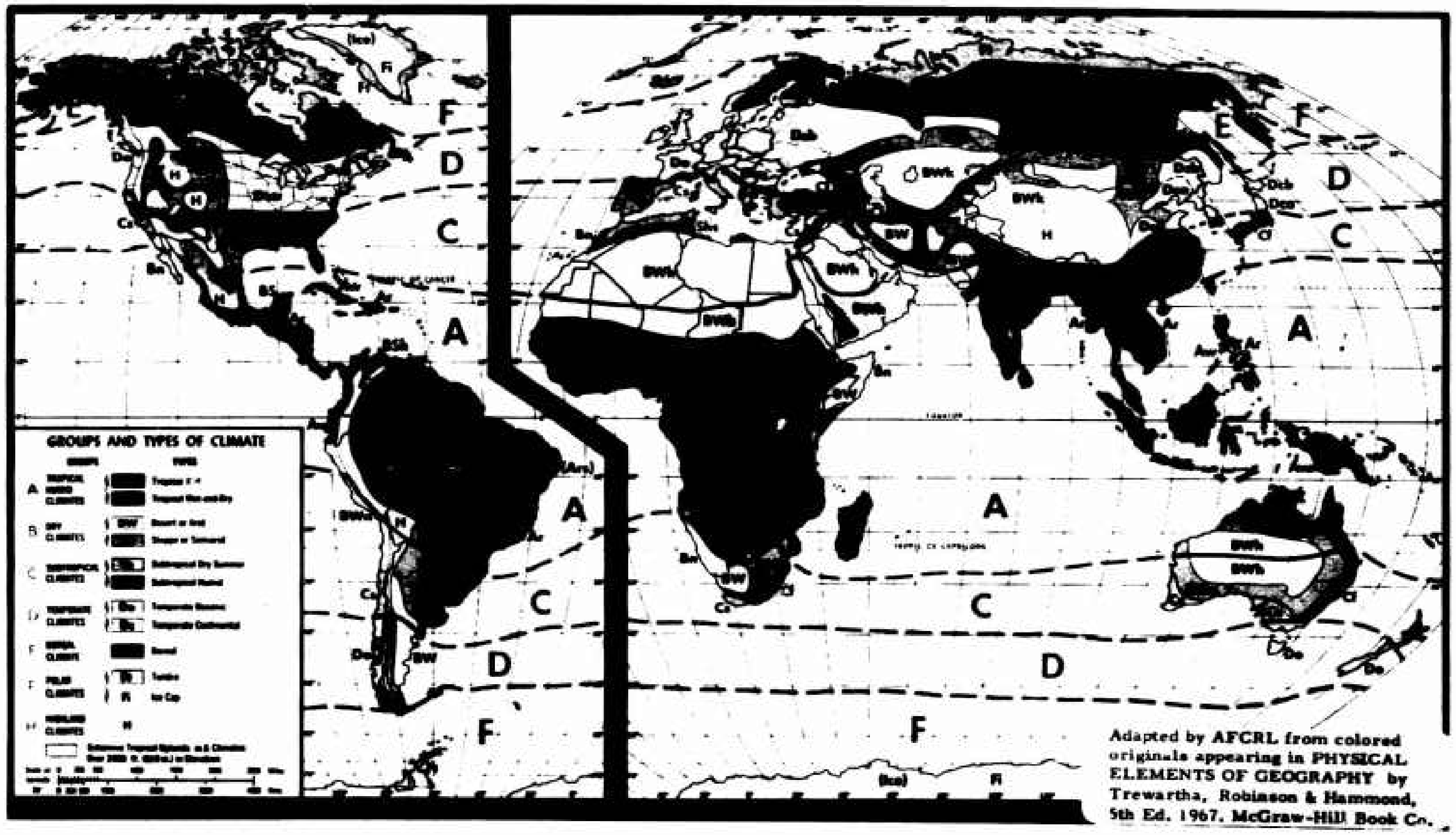


Figure B-8. Climate (World Distribution)

Table B-2. Igneous Rocks

Texture	Composition		
	Acidic Rocks (more than 50 percent silica)		Basic Rocks (less than 50 percent silica)
	Light-colored minerals, chiefly feldspar, predominate		Dark-colored minerals predominate
	Abundant quartz	Little or no quartz	Abundant amphibole pyroxene, and plagioclase feldspar
Coarse-grained (mineral crystals easily visible to naked eye).	Granite	Diorite	Gabbro
Fine-grained (mineral crystals generally invisible to naked eye).	Rhyolite	Andesite*	Basalt*
Glassy	Obsidian, pitchstone, pumice		

* Sometimes called traprock.

2.2.2 CLASSIFICATION OF SEDIMENTARY ROCKS

Sedimentary rocks (Table B-3) are classified as clastic, pyroclastic, chemical, or organic, based upon the mode of origin of the sediment from which they are derived. The clastic rocks commonly show separate grains. The chemical precipitates and evaporates, on the other hand, either have interlocking crystals or are in earthy masses. The organically formed rocks commonly contain easily recognized animal and plant remains, such as shells, bones, stems, or leaves.

2.2.3 CLASSIFICATION OF COMMON METAMORPHIC ROCKS

Metamorphic rocks (Table B-4), on the basis of their primary structure, are readily divided into two descriptive groups: the foliates and non-foliates. The foliated metamorphic rocks display a pronounced primary structure, as they have a banded appearance from the differential pressures to which they have been subjected. The nonfoliated or massive metamorphic rocks exhibit no primary structural features. These structural differences are used as the basis for the simplified classification of the common metamorphic rocks.

Table B-3. Sedimentary Rocks

Type	Sediment	Rock
Clastic or fragmental	Coarse (gravel) Medium (sand) Fines (silt and clay)	Conglomerate Sandstone Siltstone and shale
Pyroclastic	Coarse (cinder) Fine (ash)	Agglomerate Tuff
Chemical precipitates and evaporites	Calcium carbonate ($CaCO_3$) Calcium magnesium carbonate ($Ca(Mg,Fe)(CO_3)$) Silicon dioxide (SiO_2) Calcium sulphate ($CaSO_4$ $2H_2O$) ($Ca\ SO_4$) Sodium Chloride (NaCl)	Limestone Dolomite Chert Gypsum anhydrite Rock salt
Organic	Calcium carbonate (animal remains) Carbon (plant remains)	Coquina, some coral rock, and chalk Coal

Table B-4. Metamorphic Rocks

FOLIATED		
Texture	Rock	Characteristics
Coarse-grained	Gneiss	Streaked or banded; imperfectly foliated
Medium-grained	Schist	Well-foliated; splits easily; generally rich in mica
Fine-grained	Slate	Splits readily into smooth sheets
NONFOLIATED AND MASSIVE		
Mineral Content	Rock	Characteristics
Chiefly quartz	Quartzite	Hard and brittle
Chiefly calcite (or dolomite)	Marble	
Chiefly hydrous magnesium silicate	Some types of serpentine	Fairly soft; green

Table B-5. Generalized Rock Properties

RATINGS OF WORKING CHARACTERISTICS

Rock Type	Abrasiveness (A–E)	Excavational Requirements (a–e)	Permeability (1–5)	Stability in Steep-walled Cuts (1–5)	Roof Strength in Tunnels (1–5)	Loading Capacity (1–5)
1. IGNEOUS						
2. Intrusive	A	e	4–5	1	1–3	1
3. Extrusive						
3a. Solidified	B–C	d–e	3–5	1	1–3	1
3b. Cemented	C–E	b–d	1–4	3–5	3–5	3–5
4. METAMORPHIC	A–C	c–e	3–5	1–3	1–3	1–3
5. SEDIMENTARY						
6. Sandstone	A–C	c–e	1–5	1–4	1–4	1–4
7. Limestone	C–D	d–e	3–5	1–3	1–3	1–3
8. Shale	C–D	c–d	4–5	4–5	3–4	3–4
9. Evaporites	D–E	b–d	2–5	3–5	4–5	3–5

SUITABILITY FOR

Rock Type	Compacted Subgrade (1–5)	Dimension Stone (1–5)	Road Metal (1–5)	Bituminous Aggregate (1–5)	Concrete Aggregate (1–5)	Fill (1–5)
1. IGNEOUS						
2. Intrusive	1–2	1	2–4	3–4	1–3	2–3
3. Extrusive						
3a. Solidified	1–2	1	1–3	1–3	1–3	2–3
3b. Cemented	4–5	3–5	4–5	4–5	5	4–5
4. METAMORPHIC	2–5	1–4	3–5	3–5	3–5	3–5
5. SEDIMENTARY						
6. Sandstone	3–5	2–4	4–5	3–5	3–5	2–5
7. Limestone	2–4	1–3	1–4	1–3	1–3	1–3
8. Shale	5	5	5	5	5	4–5
9. Evaporites	5	5	5	5	5	5

Modified from von Bulow (Ref. 22)

Abrasiveness (as it affects excavation tools and equipment):

- A. Extreme
- B. Severe
- C. Moderate
- D. Slight
- E. Nominal or none

Tools and procedures required to excavate rock:

- a. Spade and shovel
- b. Pick and shovel
- c. Pick, crowbar, and wedge
- d. Repeated drilling and blasting
- e. Almost continuous drilling and blasting

All other properties:

1. Excellent
2. Good
3. Adequate or fair
4. Poor or usable only in emergencies
5. Inadequate, unsuitable or absent

2.3 Soil Classification

Most soil classification systems are based on grain size analysis, with arbitrary limits of grain sizes set for different soil groups. These major soil categories are gravels and sands (coarse-grained soils), silts and clays (fine-grained), and organics. The percentage of each particular type (gravel, sand, silt, or clay) in a composite soil determines the classification of the soil. Some classification systems describe the identified soil constituents, and others determine the engineering properties of a soil.

Of the eight or more methods developed for classifying soils, three systems — Unified Soil Classification System, Agricultural Soil Classification System, and Geologic Soil Classification System — are the most commonly used.

2.3.1 UNIFIED SOIL CLASSIFICATION SYSTEM

This system, known as the USCS, classifies the physical properties of soil for engineering purposes (see Tables B-6, B-7, and Figure B-8). It lists eight groups of coarse-grained soils, six groups of fine-grained soils, and one group of organic soils.

Identification and classification are based upon grain size, mechanical analysis, plastic limit tests, and other physical properties.

2.3.2 AGRICULTURAL SOIL CLASSIFICATION SYSTEM

This system, known as USDA, classifies surface soils for agricultural purposes (Figure B-9). Based on physical properties and specific percentages of gravel, sand, silt, and clay in a composite soil, the potential agricultural productivity of a soil can be determined. The soil properties also reflect the influence of geologic processes, age, climate, vegetation, and topographic features. Figure 2 in the report lists the gradation limits of soil for use with Figure B-9.

2.3.3 GEOLOGIC SOIL CLASSIFICATION SYSTEM

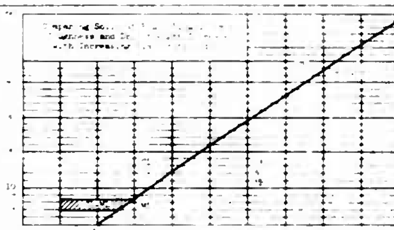
This system is based upon the geologic origin of soils. The major divisions of residual and transported soils by landform features are glacial, fluvial (stream-laid), eolian (wind blown), lacustrine (water), littoral (shore), and volcanic.

The Wentworth Scale is used to classify a soil or rock by grain size gradation from boulders to fine-grained soils, as listed in Figure 2 in the report (Leet and Judson, 1965, p. 98).

Table B-6. Unified Soil Classification System

UNIFIED SOIL CLASSIFICATION (Including Identification and Description)

Major Divisions			Group Symbols	Typical Names	Field Identification Procedures (Excluding particles larger than 3 in. and basing fractions on estimated weights)			Information Required for Describing Soils	Laboratory Classification Criteria
1	2		3	4	5			6	7
Coarse-grained Soils. More than half of material is larger than No. 200 sieve size. The No. 200 sieve size is about the smallest particle visible to the naked eye	Gravels. More than half of coarse fraction is larger than No. 4 sieve size. (For visual classification, the 1/4-in. size may be used as equivalent to the No. 4 sieve size)	Clean Gravels (Little or no fines)	GW	Well-graded gravels, gravel-sand mixtures, little or no fines	Wide range in grain size and substantial amounts of all intermediate particle sizes			[illegible]	[illegible]
			GP	Poorly graded gravels or gravel-sand mixtures, little or no fines	Predominantly one size or a range of sizes with some intermediate sizes missing				
		Gravels with Fines (Appreciable amount of fines)	GM	Silty gravels, gravel-sand-silt mixture.	Nonplastic fines or fines with low plasticity (for identification procedures see ML below)			[illegible]	
			GC	Clayey gravels, gravel-sand-clay mixtures	Plastic fines (for identification procedures see CL below)				
	Sands. More than half of coarse fraction is smaller than No. 4 sieve size	Clean Sands (Little or no fines)	SW	Well-graded sands, gravelly sands, little or no fines	Wide range in grain size and substantial amounts of all intermediate particle sizes				
			SP	Poorly graded sands or gravelly sands, little or no fines	Predominantly one size or a range of sizes with some intermediate sizes missing.				
		Sands with Fines (Appreciable amount of fines)	SM	Silty sands, sand-silt mixtures	Nonplastic fines or fines with low plasticity (for identification procedures see ML below)			[illegible]	
			SC	Clayey sands, sand-clay mixtures	Plastic fines (for identification procedures see CL below).				
					Identification Procedures on Fraction smaller than No. 40 Sieve Size				
					Dry Strength (Crushing characteristics)	Dilatancy (Reaction to shaking)	Toughness (Consistency near PL)		
Fine-grained Soils. More than half of material is smaller than No. 200 sieve size.	Silts and Clays. Liquid limit is less than 50		ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity	None to slight	Quick to slow	None	[illegible]	[illegible]
			CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	Medium to high	None to very slow	Medium		
			OL	Organic silts and organic silty clays of low plasticity	Slight to medium	Slow	Slight	[illegible]	
	Silts and Clays. Liquid limit is greater than 50		MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	Slight to medium	Slow to none	Slight to medium		
			CH	Inorganic clays of high plasticity, fat clays	High to very high	None	High		
			OH	Organic clays of medium to high plasticity, organic silts	Medium to high	None to very slow	Slight to medium	[illegible]	
Highly Organic Soils			Pt	Peat and other highly organic soils	Readily identified by color, odor, spongy feel and frequently by fibrous texture				



(1) Boundary classifications: Soils possessing characteristics [illegible]

FIELD IDENTIFICATION PROCEDURES FOR FINE-GRAINED SOILS OR FRACTIONS

[illegible]

Dilatancy (reaction to shaking)

After removing particles larger than No. 40 sieve size, prepare a pat of moist soil with a volume of about one-half cubic inch. [illegible]

Dry strength (crushing characteristics)

[illegible]

Toughness (consistency near plastic limit)

[illegible]

AFM 88-52

Adapted by Corps of Engineers and Bureau of Reclamation [illegible]

Table B-7. Characteristics Pertinent to Roads and Airfields

Major Divisions (1)	(2)	Letter (3)	Symbol: Hatching (4)	Symbol: Color (5)	Name (6)	Value as Foundation When Not Subject to Frost Action (7)	Value as Base Directly under Bituminous Pavement (8)	Potential Frost Action (9)	Compressibility and Expansion (10)	Drainage Characteristics (11)	Compaction Equipment (12)	Unit Dry Weight Lb Per Cu Ft (13)	Field CBR (14)	Subgrade Modulus k, Lb Per Cu In. (15)
COARSE GRAINED SOILS	GRAVEL AND GRAVELLY SOILS	GW		Red	Well-graded gravels or gravel-sand mixtures, little or no fines	Excellent	Good	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired equipment, steel-wheeled roller	125-140	60-80	300 or more
		GP		Red	Poorly graded gravels or gravel-sand mixtures, little or no fines	Good to excellent	Poor to fair	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired equipment, steel-wheeled roller	110-130	25-60	300 or more
		GM d		Yellow	Silty gravels, gravel-sand-silt mixtures	Good to excellent	Fair to good	Slight to medium	Very slight	Fair to poor	Rubber-tired equipment, sheepsfoot roller; close control of moisture	130-145	40-80	300 or more
		GM u		Yellow		Good	Poor	Slight to medium	Slight	Poor to practically impervious	Rubber-tired equipment, sheepsfoot roller	120-140	20-40	200 to 300
		GC		Yellow	Clayey gravels, gravel-sand-clay mixtures	Good	Poor	Slight to medium	Slight	Poor to practically impervious	Rubber-tired equipment, sheepsfoot roller	120-140	20-40	200 to 300
	SAND AND SANDY SOILS	SW		Red	Well-graded sands or gravelly sands, little or no fines	Good	Poor	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired equipment	110-130	20-40	200 to 300
		SP		Red	Poorly graded sands or gravelly sands, little or no fines	Fair to good	Poor to not suitable	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired equipment	100-120	10-25	200 to 300
		SM d		Yellow	Silty sands, sand-silt mixtures	Good	Poor	Slight to high	Very slight	Fair to poor	Rubber-tired equipment sheepsfoot roller; close control of moisture	120-135	20-40	200 to 300
		SM u		Yellow		Fair to good	Not suitable	Slight to high	Slight to medium	Poor to practically impervious	Rubber-tired equipment, sheepsfoot roller	105-130	10-20	200 to 300
		SC		Yellow	Clayey sands, sand-clay mixtures	Fair to good	Not suitable	Slight to high	Slight to medium	Poor to practically impervious	Rubber-tired equipment, sheepsfoot roller	105-130	10-20	200 to 300
FINE GRAINED SOILS	SILTS AND CLAYS LL < 50	ML		Green	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity	Fair to poor	Not suitable	Medium to very high	Slight to medium	Fair to poor	Rubber-tired equipment, sheepsfoot roller; close control of moisture	100-125	5-15	100 to 200
		CL		Green	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	Fair to poor	Not suitable	Medium to high	Medium	Practically impervious	Rubber-tired equipment, sheepsfoot roller	100-125	5-15	100 to 200
		OL		Green	Organic silts and organic silt-clays of low plasticity	Poor	Not suitable	Medium to high	Medium to high	Poor	Rubber-tired equipment, sheepsfoot roller	90-105	4-8	100-200
	SILTS AND CLAYS LL > 50	MH		Blue	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	Poor	Not suitable	Medium to very high	High	Fair to poor	Sheepsfoot roller	80-100	4-8	100 to 200
		CH		Blue	Inorganic clays of high plasticity, fat clays	Poor to very poor	Not suitable	Medium	High	Practically impervious	Sheepsfoot roller	90-110	3-5	50 to 100
		OH		Blue	Organic clays of medium to high plasticity, organic silts	Poor to very poor	Not suitable	Medium	High	Practically impervious	Sheepsfoot roller	80-105	3-5	50 to 100
HIGHLY ORGANIC SOILS		Pt		Orange	Peat and other highly organic soils	Not suitable	Not suitable	Slight	Very high	Fair to poor	Compaction not practical	-	-	-

Notes:

1. Column 3, Division of GM, and SM groups into subdivisions of d and u are for roads and airfields only; subdivision is on basis of Atterberg limits; suffix d (e.g., GMd) will be used when the liquid limit is 28 or less and the plasticity index is 6 or less; the suffix u will be used when the liquid limit is greater than 28.
2. Column 7, values are for subgrades and base courses except for base course directly under bituminous pavement.
3. In column 8, the term "excellent" has been reserved for base materials consisting of high quality processed crushed stone.
4. In column 9, these soils are susceptible to frost as indicated under conditions favorable to frost action described in the text.
5. In column 12, the equipment listed will usually produce the required densities with a reasonable number of passes when moisture conditions and thickness of lift are properly controlled. In some instances, several types of equipment are listed, because variable soil characteristics within a given soil group may require different equipment. In some instances a combination of two types may be necessary.
   a. Processed base materials and other angular materials. Steel-wheeled rollers are recommended for hard angular materials with limited fines or screenings. Rubber-tired equipment is recommended for softer materials subject to degradation.
   b. Finishing. Rubber-tired equipment is recommended for rolling during final shaping operations for most soils and processed materials.
   c. Equipment size. The following sizes of equipment are necessary to assure the high densities required for airfield construction:
      Crawler-type tractor — total weight in excess of 30,000 lb.
      Rubber-tired equipment — wheel load in excess of 15,000 lb, wheel loads as high as 40,000 lb may be necessary to obtain the required densities for some materials (based on contact pressure of approximately 65 to 150 psi).
      Sheepsfoot roller — unit pressure (on 6- to 12-sq-in. foot) to be in excess of 250 psi and unit pressures as high as 650 psi may be necessary to obtain the required densities for some materials. The area of the foot should be at least 5 percent of the total peripheral area of the drum, using the diameter measured to the faces of the feet.
6. Column 13, unit dry weights are for compacted soil at optimum moisture content for modified AASHO compactive effort.

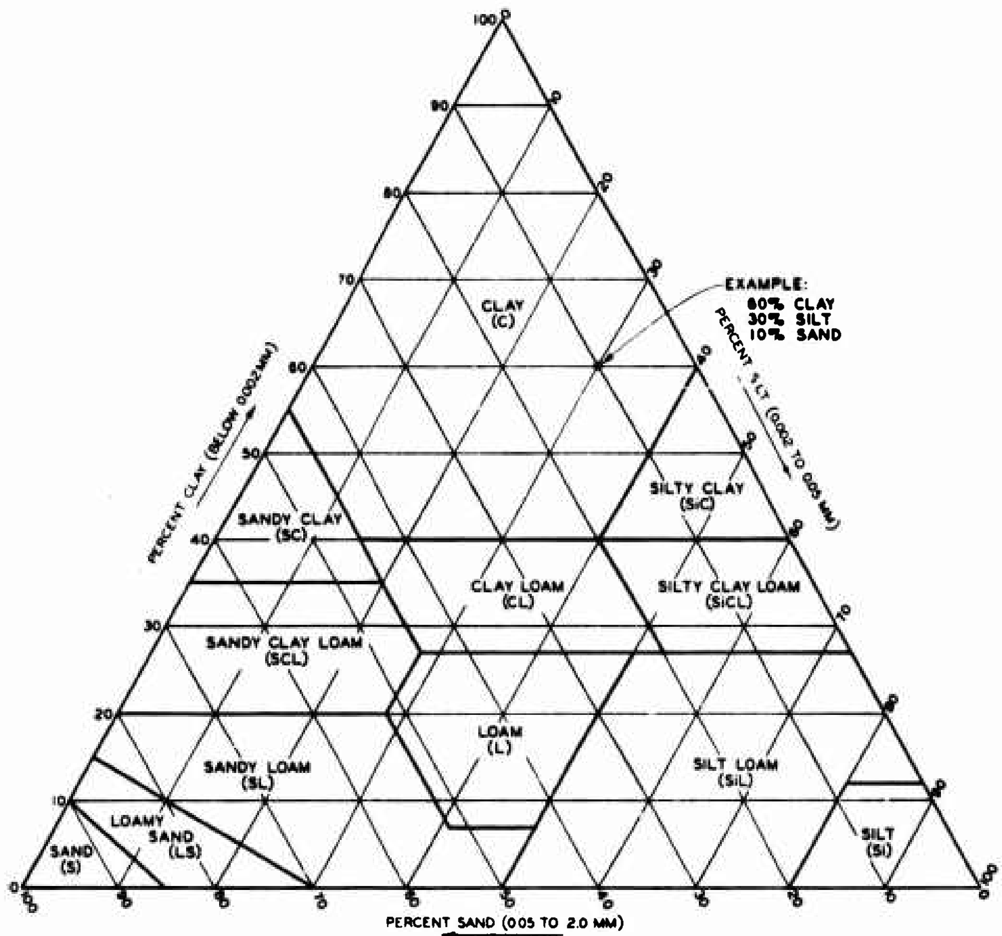


Figure B-9. USDA Soil Textural Classification

2.3.4 CORRELATION OF SOIL CLASSIFICATION SYSTEMS

With certain limitations, laboratory analysis of soil samples has shown that a general correlation exists between the USCS and USDA soil types (U. S. Army C.E.WES, TM 3-240, 16th Supplement). Of 1176 samples classified, many categories of the USDA Agricultural Soil Classification System can be correlated with the soil groups of the Unified Soil Classification System. The correlations range from 41 to 100 percent, the average being about 60 percent. See Table B-8. The grain size and soil groups of the USDA, USCS, and Wentworth systems are shown in Figure 2 in the report to be in close agreement.

Table B-8. Frequency of USDA Types Occurring as USCS Soil Types

USDA Soil Type			USCS Soil Type															
			Coarse-Grained Soils with Fines						Fine-Grained Soils					Organic Soils			Total	
			GM	GC	[illegible]	SM	SM-SC	SC	ML	CL-ML	MH	CL	CH	OL	OH	Pt	%	n
Sandy Soils	S†	%			[illegible]	[illegible]	[illegible]										100	
		n			21	[illegible]	1											44
	LS	%				[illegible]		[illegible]									100	
		n				[illegible]												57
	SL†	%	*			41	[illegible]	[illegible]	[illegible]	4		[illegible]		2	2		100	
		n	1			[illegible]	[illegible]	[illegible]				[illegible]		5	4			207
	SCL	%				11	[illegible]	[illegible]				[illegible]					100	
		n					1					[illegible]						[illegible]
	SC	%										50					100	
		n																2
Clayey, Silty, and Loamy Soils	Lt	%	*	*					[illegible]	11	*	[illegible]	[illegible]	[illegible]	[illegible]		100	
		n		1					[illegible]	[illegible]	1	[illegible]		[illegible]	1			[illegible]
	SiL	%							[illegible]	[illegible]	[illegible]	45	[illegible]	[illegible]	[illegible]		100	
		n							172	[illegible]	[illegible]	215	[illegible]		[illegible]			[illegible]
	Si	%							[illegible]								100	
		n							[illegible]			1						11
	CL	%									[illegible]	[illegible]	[illegible]		[illegible]		100	
		n							[illegible]		1	[illegible]	[illegible]		1			[illegible]
	SiCL	%							[illegible]	1	1	67	27		3		100	
		n							1	1	1	[illegible]	[illegible]		2			[illegible]
	SiC	%							[illegible]			24	[illegible]				100	
		n							[illegible]			[illegible]	[illegible]					21
	C	%							[illegible]		10	[illegible]	[illegible]		[illegible]		100	
		n							[illegible]		[illegible]	[illegible]	[illegible]		[illegible]			[illegible]
Organic Soil	Pt	%														[illegible]	100	
		n																[illegible]
Total samples																		[illegible]

n Number of samples.
* Less than 1%.
† Prefixed with the term gravelly, cobbly, or stony for GM or GC soil types.

	CL
SiL	45
	215

Sample Interpretation

45% of all SiL samples were CL. The circle indicates that a greater number of SiL samples occurred as CL than as any other USCS type. 215 samples were classified as SiL and CL.

3. BEARING STRENGTH OF TERRAIN AND SOIL

An index of trafficability for most ground vehicles is the wet season characteristics of soil and generally trafficable vegetation as shown in Table B-9. Most dry soils and certain saturated fine-grained soils have a relatively high resistance to penetration, while many physical properties contribute to the bearing strength of a soil.

The primary determinant of bearing strength is the nature of the surface materials — its density, grain size and shape, moisture content, and vegetation — which are measured in standard engineering terms of the California Bearing Ratio applied to soil and rock strength. Moisture affects the strength of some soils severely (Figure B-10).

The distribution of soil-strength regions in the world (Figure B-11) show five qualitative divisions for trafficability conditions based on an interpretation and evaluation of Figures B-1, B-5, B-6, B-7, B-9, and B-10. The divisions are: (1) soft ground most of the time, (2) soft ground and firm ground alternating all year, (3) seasonality of soft and firm ground, (4) season of firm ground and season of alternating firm and soft ground, and (5) firm ground most of the time. About 78 percent of the land area of the world has a firm soil with a Rating Cone Index exceeding 60; 17 percent has a soft soil with a RCI of from 25 to 60; and 5 percent has a very soft soil with a RCI of less than 25.

3.1 California Bearing Ratio (CBR)

The California Bearing Ratio is the most reliable engineering test for measuring the shearing and traction resistance of a soil under controlled conditions of density and moisture (AFM 88-52, AFM 88-51, TM 5-541). Refer to Appendix C of this report for further information.

3.2 Terrain and Soil as Foundation Materials

For guidance in the design of major facilities and structures, an estimation of the maximum allowable loading values, in tons per square foot, is shown in Table B-10 for all types of rocks and soils (Aviation Egr. Force, 1956). These values vary from 1 ton PSF to over 40, but do not apply if the foundation is underlain by a weaker material. Controlled laboratory and field tests of representative samples obtained from the proposed site are always recommended prior to construction (AFM 88-52, p. 286).

Table B-9. Trafficability Characteristics of USCS Soils in Wet Season

Class	Soils	USCS Soil Type	Probable CI Range	Probable RI Range	Probable RCI Range	Slipperiness Effects	Stickiness Effects	Comments
A	Coarse-grained, cohesionless sand and gravels	GW, GP SW, SP	80 to 300	1	80 to 300	Slight to none	None	Will support continuous traffic of military vehic[illegible] tracks or with hi[illegible] tires. Moist san[illegible] dry sand only fair. Wheeled vehicles with standard tires may be immobilized in dry sands
B	Inorganic clays of high plasticity, fat clays	CH	55 to 165	0.75 to 1.35	65 to 140	Severe to slight	Severe to slight	Usually will support more than 50 passes of military vehicles. Going will be difficult at times
C	Clayey gravels, gravel-sand-clay mixture	GC	85 to 175	0.45 to 0.75	45 to 125	Severe to slight	Moderate to slight	Often will not support 40 to 50 passes of military vehicles, but usually will support unlimited traffic. Going will be difficult in most cases
	Clayey sand, sand-clay mixtures	SC						
	Gravelly clays, sandy clays, inorganic clays of low to medium plasticity, lean clays, silty clays	CL						
D	Silty Gravels, gravel-sand-silt mixtures	GM	85 to 180	0.25 to 0.85	25 to 120	Moderate to slight	Slight	Usually will not support 40 to 50 passes of military vehicles. Often will not permit even a single pass. Going will be difficult in most cases
	Silty sands, sand-silt mixtures	SM						
	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity	ML and CL-ML						
	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	MH						
	Organic silts and organic silty clays of low plasticity	OL						
	Organic clays of medium to high plasticity, organic silts	OH						
E	Peats and mucks	Pt	10 to 100	0.25 to 0.65	10 to 85	Slight to none	Moderate to slight	Often will not permit even a single pass. Going will be difficult to impossible

Note: Taken from Trafficability of Soils, A Summary of Trafficability Studies Through 1955, TM No. 3-240, 14th Supplement, December 1956

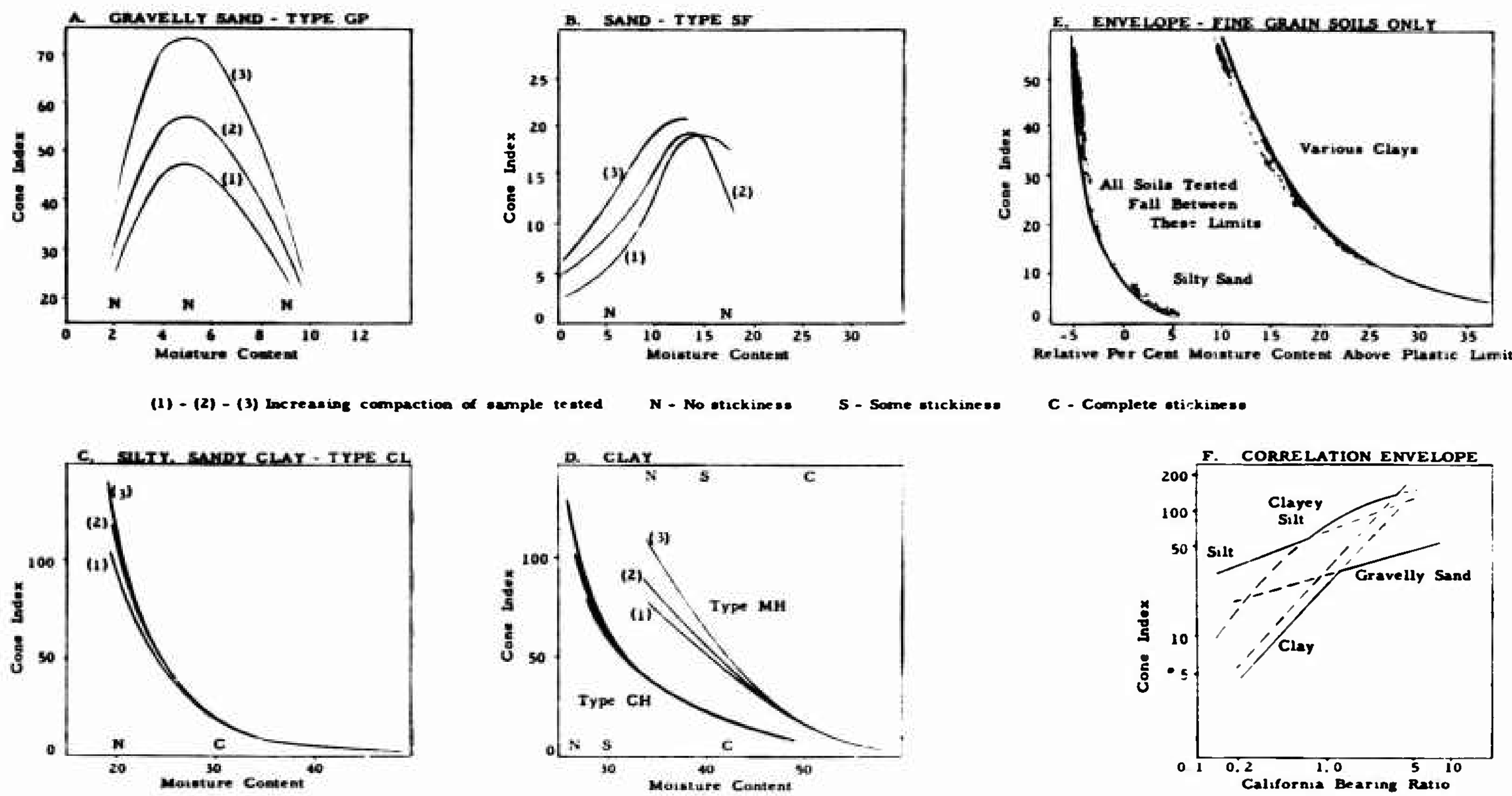


Figure B-10. Variation of Soil Strengths With Moisture Content and Correlation of Cone Index With California Bearing Ratio

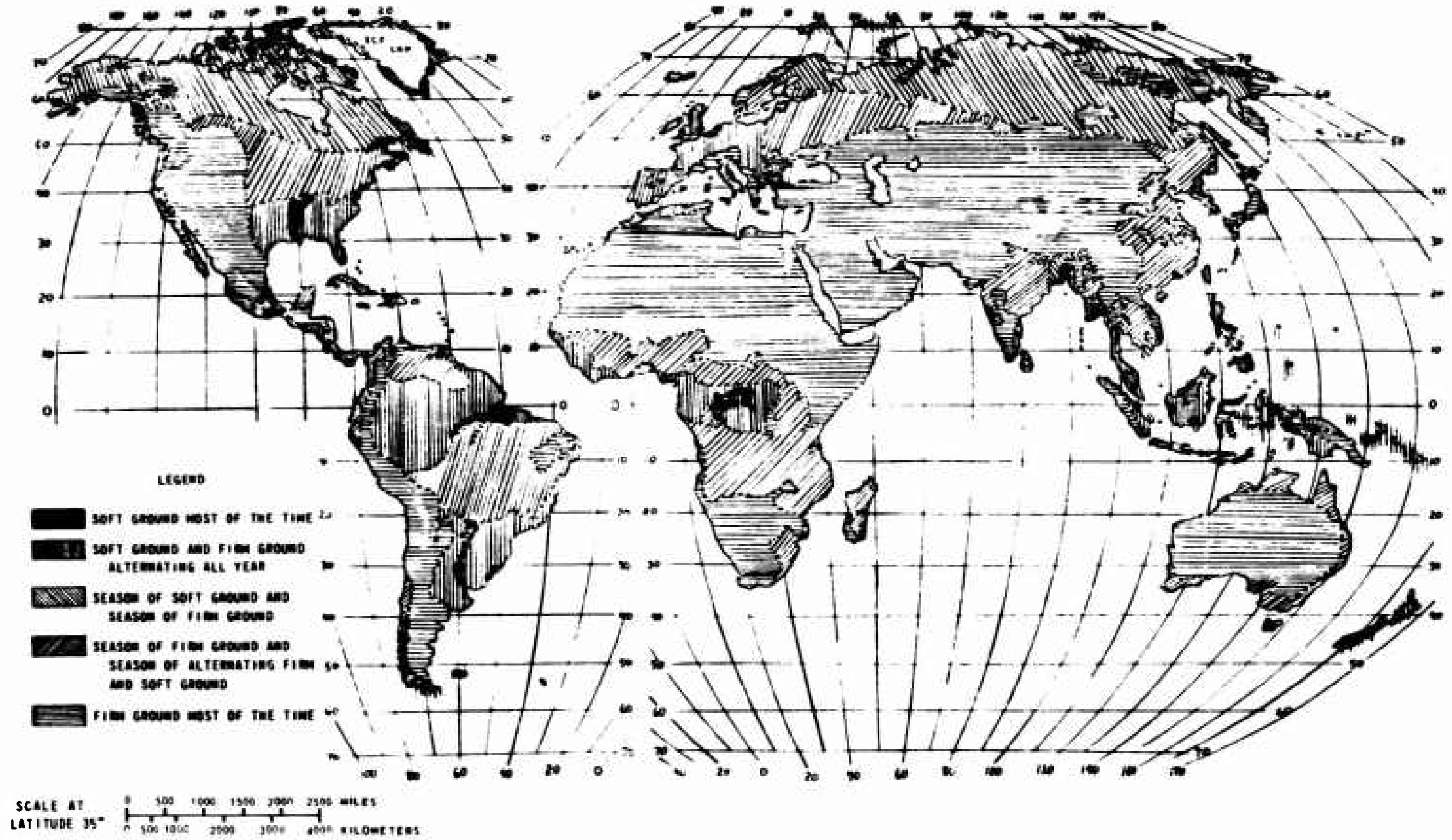


Figure B-11. Soil Strength Regions (World Distribution)

Table B-10. Allowable Pressures for the Design of Shallow Foundations

	Maximum allowable pressure, tons per square foot
Hard, sound rock	40+
Soft rock	8-10
Hardpan overlying rock	10-12
Compact gravel and boulder-gravel deposits; very compact sandy gravel	10
Loose gravel and sandy gravel; compact sand and gravelly sand; very compact inorganic sand-silt soils	5-6
Hard, dry, consolidated clay	5
Loose coarse to medium sand; medium compact fine sand	4
Compact sand-clay soils	3
Loose fine sand; medium compact inorganic sand-silt soils	2
Firm or stiff clay	1.5-2
Loose saturated sand-clay soils; medium soft clay	1

Note. Values are not applicable if foundation soil is underlain by a weaker soil. Use of the tabular values for the design of shallow foundations of major structures is not recommended unless their use is justified by experience or additional investigation.

Appendix C

Data Acquisition and Representative Applied Processing

1. INTRODUCTION

Terrain data acquired by either the contact, non-contact, or indirect method can be digitized conveniently to characterize the factor groups and their subclasses. This permits their amenability to computer system programming (processing, storage, retrieval, analysis, and presentation phases). In data processing terms, the application (that is, the specifications of proposed use of the terrain being evaluated) and the terrain factors (designators) constitute the input; the result of their interaction is the evaluation model; and the measure of predicted performance under a given set of environmental conditions is the output. The description of the tests, nomenclature of equipment, and computer models of specific cases are beyond the scope of this report. The computer approach is applicable to a broad spectrum of military uses.

2. CONTACT METHOD

The field measurement of all terrain factors and their subclasses is done with standard testing and sampling equipment and by procedures that are described in detail in the literature. Some new equipment used is described in Section 5 below.

With the contact method, each critical value of the specified terrain factor and its subclass at the surface and subsurface is measured and mapped precisely for total data quantification. Such data can be used directly for computerized storage or applied to the model of the required use. The data also can serve as ground controls and clues to the non-contact imagery.

3. NON-CONTACT METHOD

Remote sensing of the terrain environment yields largely qualitative but some semi-quantitative information. Figure 10 in the report indicates the type of sensors used and the extensive instrumentation necessary for acquiring and interpreting the data. These sensors are aerial photography in the ultraviolet, visible, and infrared; radar; radio waves; and instrumentation in air-drop devices. The references on remote sensing are numerous; the reader is referred to a selected list in the bibliography under a special heading, Remote Sensing Publications.

4. INDIRECT METHOD

The indirect method of terrain-data acquisition is often employed to estimate the critical terrain factor class values. Highly trained individuals can infer, evaluate, and predict terrain characteristics and expected performance of a military activity through analysis of data acquired by this method.

This method utilizes standard photographic and photogrammetric devices, data obtained from the contact and non-contact methods, library source data, and the skills of regional, scientific, and technical specialists.

5. DEVICES FOR MEASURING BEARING STRENGTH OF TERRAIN PROFILE

The terrain factor subclass affecting the trafficability and load-bearing capacity of a soil is its shear strength. Although vegetation and its root structure, interbedded rock and gravel, and other terrain properties influence its strength, the measured shearing resistance of a soil mainly indicates its degree of ability to support military air and ground operations, such as aircraft and vehicular trafficability.

5.1 Cone Penetrometers

Several types of penetrometers have been developed to measure the soil shearing and traction resistance for the trafficability evaluation of unsurfaced areas (TM 3-240, Supp. 1; USA WES Landing Strip Evaluation, 1952). In Figure C-1, penetrometer measurements of fine-grained soils, in units of cone index, are conservatively correlated with CBR criteria of specific calibrated soil types.

Vehicle and aircraft trafficability and other requirements for composite or single-soil load-bearing strengths are based upon direct CBR or CBR-equivalent values (Figure C-2). Further refinement of CBR-equivalent correlations of penetrometer index values for different soils will narrow the deviation from directly measured CBR data (Molineux, 1955; USA WES Misc. Paper 4-101).

Variation of soil strength with moisture content and correlations of cone index of selected classified soil types with CBR-equivalents are illustrated in Figures B-10 and C-1. The cone index shown in the curves refers to the Army Engineer proving ring penetrometer criteria, unless otherwise designated as the tension spring model.

5.1.1 SHEAR STRENGTH CONE INDEX

Any air-drop or ground cone penetrometer measures the cone index, and this measurement is correlated with the California Bearing Ratio (CBR) by soil type, as classified by the USCS System, to obtain CBR-equivalent units.

Basically, a penetrometer is a bearing-strength measuring device consisting of a 30-deg circular cone mounted on the end of a steel shaft; the cone normally has a base end area of 0.5 sq in. The force required for the cone to penetrate the ground surface is indicated on a dial or on an engraved scale. Generally, air-drop models are previously calibrated to shear a pin of known cone index. The use and design of the penetrometer (proving ring) and related test equipment, including the manual, linear, coiled-tension-spring model (150- and 300-lb models) are completely described in AFM 88-51, p. 93. The proving ring model has a dial ranging from 0 to 300 (Figure C-3). The value 300 occurs under a force of 150 lb. The spring model is read directly in pounds of force, with a maximum limit of 300 lb (Figure C-4).

Air-drop devices are treated in Chapter III, Remote Sensing.

5.1.2 AUTOMATIC RECORDING CONE PENETROMETER

An automatic recording model based on the original 300-lb spring-load design model was developed by Air Force Cambridge Research Laboratories and is

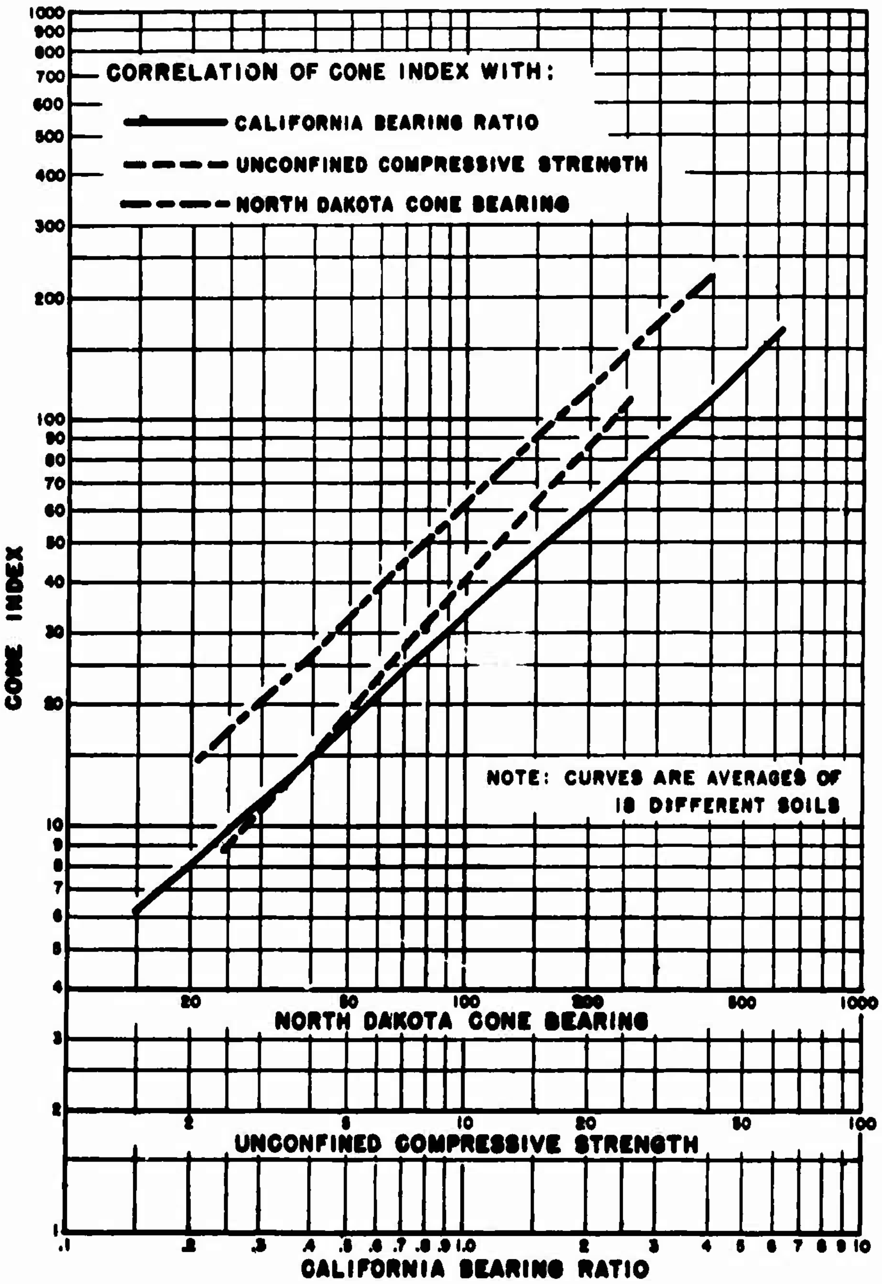


Figure C-1. Relation of Cone Index to California Bearing Ratio, Unconfined Compressive Strength, and North Dakota Cone Bearing Strength

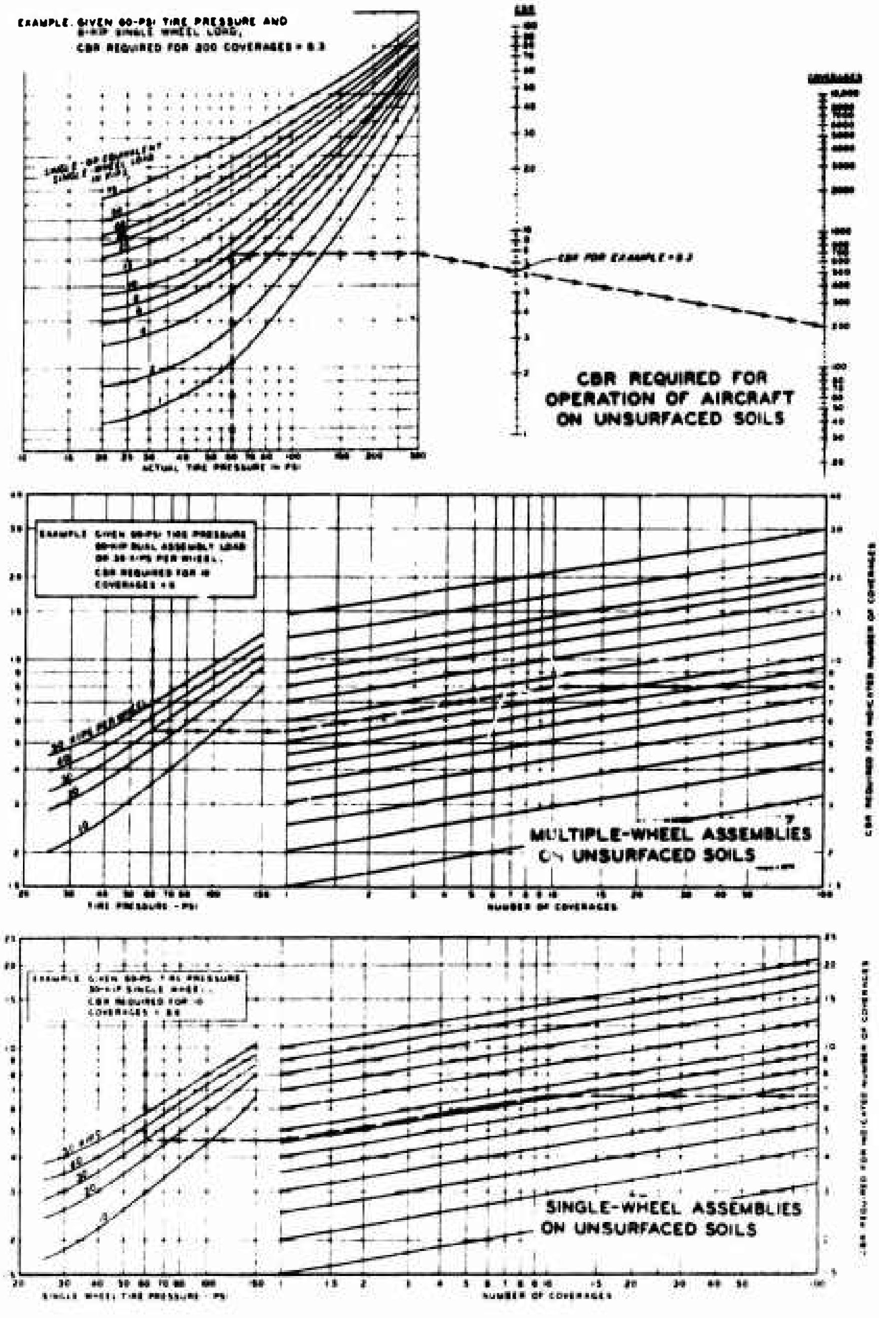


Figure C-2. California Bearing Ratio Required for Operation of Aircraft on Unsurfaced Soils by Wheel Load, Tire Pressure, and Traffic in Coverages

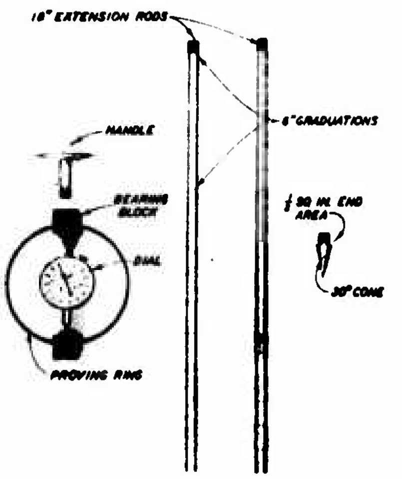


Figure C-3. Proving Ring Manual Cone Penetrometer

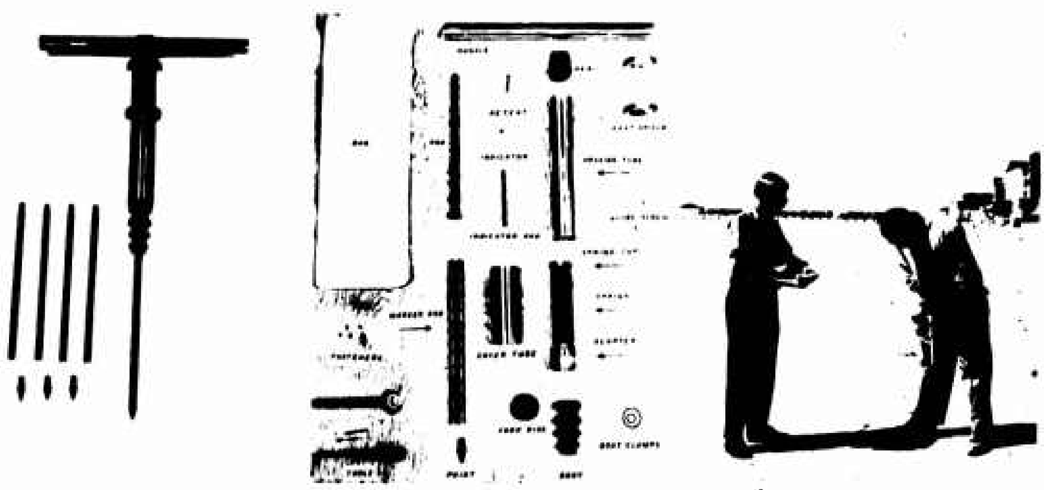


Figure C-4. AFCRL Tension Spring Manual Cone Penetrometer

shown in Figure C-5. It incorporates all the features of the AFCRL manual airfield penetrometer, in addition to having the capability of recording and providing strength-thickness information automatically and immediately. The most important improvement is that the maximum soil load-bearing-strength measurement has been extended to a CBR (equivalent) of over 70. An added feature is that this instrument can be operated in darkness.

This model retains the standard 30-deg cone tip mounted on a 20-in.-long, 7/16-in. shaft. A spring-loaded chain-drive action is proportional to the load applied to the cone. A maximum of 600 lb is designed for the spring load. Dual cranker levers drive the rod-mounted cone into the soil. Data are rapidly obtained as a permanent record. The instrument can be operated by non-professional personnel.

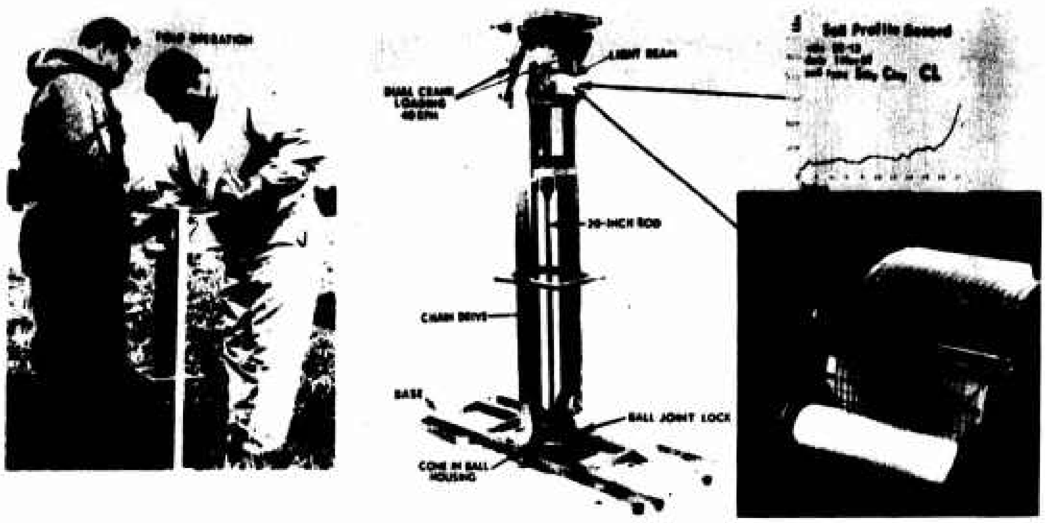


Figure C-5. AFCRL Automatic Recording Cone Penetrometer (600 lb Model)

6. MATRIX DESIGNATOR METHOD

A class value coding system of digitized terrain parameters (matrix groups) can be used to describe an area of interest for military operations. Within each matrix group, the associated parameters are sub-divided into classes to designate the characteristic features in terms of the primary and secondary parameter groups, depending upon the application. Matrix coding can be increased to characterize complex terrain conditions more accurately. The system permits the flexibility for extending parameter limits, modifying categories, and adding new parameters.

6.1 Matrix Composition

Each matrix group is composed of several classes selected to meet the requirements for terrain information. A single terrain factor is divided into a number of matrix class ranges with an assigned class designator in an arrangement of sequential coding (Bredhal and Kiefer, 1957, p. 40).

6.2 Description of Natural Unprepared Landing Surface by Matrix Format

The system for describing landing areas establishes a minimum of five matrix groups, each of which is described by a class-designator code for the selected related factors. These groups and subclasses, as summarized in Tables C-1 to C-7, are suitable for describing any area in a global terrain environment.

Table C-1. Terrain Matrix Classes of Landing Areas

Matrix	Parameter Group	Parameter Subclass	Class Designator Code	Table of Class Designators
Group I (3 Digits)	Landing Area	Length (Ft) Width Slope (Deg) Length Slope (Deg)	1st & 2nd Digits 3rd Digit 4th Digit	Table C-2
Group II (3 Digits) 1st Group Designator Code	Terrain Surface	Primary Undulation[1] Height Primary Undulation Slope Primary Undulation Spacing Type of Undulation	1st Digit 2nd Digit 3rd Digit Subscript Letter	Table C-3 Table C-4
2nd Group Designator Code		Secondary Undulation Height Secondary Undulation Slope Secondary Undulation Spacing Type of Undulation	1st Digit 2nd Digit 3rd Digit Subscript Letter	
3rd Group	If warranted for Complete Classification			
Group III (2 Digits) 1st Group Designator Code	Surface Roughness (Obstacle)	Primary Obstacle Height Primary Obstacle Spacing Type of Obstacle	1st Digit 2nd Digit Subscript Letter	Table C-5
2nd Group Designator Code		Secondary Obstacle Height Secondary Obstacle Spacing Type of Obstacle	1st Digit 2nd Digit Subscript Letter	
3rd Group Designator Code	If warranted for Complete Classification			
Group IV (4 Digits)	Soil Type and Bearing Strength	Soil Type (USCS) Bearing Strength Dust, Ice, Snow, Water Conditions	1st & 2nd Digit 3rd & 4th Digit Subscript Letter	Table C-6
Group V (3 Digits)	Utilization	Type of Aircraft Trafficability	1st & 2nd Digit 3rd Digit	Table C-7

[1] Negative undulations below horizontal reference plane have minus sign.

Table C-2. Matrix I - The Landing Area

AREA LENGTH (1st and 2nd Digits - Matrix I)	
Class Designator	**Actual Length Available (feet)**
00	> 10000
01	8000 - 10000
02	6500 - 8000
03	5000 - 6500
04	4000 - 5000
05	3000 - 4000
06	2500 - 3000
07	2000 - 2500
08	1500 - 2000
09	1000 - 1500
10	900 - 1000
11	800 - 900
12	700 - 800
13	600 - 700
14	500 - 600
15	400 - 500*
16	300 - 400*
17	200 - 300*
18	100 - 200*
19	50 - 100*

WIDTH SLOPE (3rd Digit - Matrix I)	
Class Designator	**Width Slope (Degrees)**
0	0 - 2
1	2 - 4
2	4 - 6
3	6 - 9
4	9 - 12
5	12 - 15
6	15 - 20
7	20 - 30
8	30 - 45
9	> 45

LENGTH SLOPE (4th Digit - Matrix I)	
Class Designator	**Length Slope (Degrees)**
0	0 - 2
1	2 - 4
2	4 - 6
3	6 - 9
4	9 - 12
5	12 - 15
6	15 - 20
7	20 - 30
8	30 - 45
9	> 45

Note - The Parameter Categories are read: from and including the shorter length and up to but not including the longer length or greater slope.

* These dimensions may be considered as area diameters unless a width limitation is indicated.

Table C-3. Matrix II - The Surface Configuration

UNDULATION HEIGHT (1st Digit - Matrix II)		UNDULATION SLOPE (2nd Digit - Matrix II)		UNDULATION SPACING (3rd Digit - Matrix II)
Class Designator	Height (Inches or feet as indicated)	Class Designator	Slope (Degrees)	Center-to-Center Distance*
0	< 3"	0	0 - 2	*See Table C-4.
1	3" - 6"	1	2 - 4	
2	6" - 12"	2	4 - 6	
3	12" - 18"	3	6 - 10	
4	18" - 24"	4	10 - 15	
5	2' - 5'	5	15 - 20	
6	5' - 10'	6	20 - 30	
7	10' - 25'	7	30 - 45	
8	25' - 50'	8	45 - 60	
9	50' - 100'	9	60 - 90	

Note - The parameter categories are read: from and including the lesser, and up to, but not including,the greater height or slope.

Descriptive Subscript Legend

C - Small Stream or Creek
D - Ditch or Embankment (cultural rather than natural formations)
E - Erosion Gullies (natural rather than cultural formations)
H - Holes (irrespective of how formed)
M - Mounds
P - Plowed, tilled or cultivated furrows
R - Roads
S - Sand Dunes or Sand Ripples
W - Undulations parallel to width
L - Undulations parallel to length

Table C-4. Matrix IIA - Center to Center Spacing

(USE IN CONJUNCTION WITH TABLE C-3)

CENTER-TO-CENTER SPACING AND CLASS DESIGNATORS FOR UNDULATION HEIGHT CATEGORIES

UNDULATION SPACING FOR HEIGHT CLASS (0) (less than 3 inches height)

Class Designator	C-to-C Distance (feet)
0	> 10
1	8 - 10
2	6 - 8
3	5 - 6
4	4 - 5
5	3 - 4
6	2 - 3
7	1 - 2
8	0.5 - 1
9	< 0.5

UNDULATION SPACING FOR HEIGHT CLASS (1) (3 - 6 inches height)

Class Designator	C-to-C Distance (feet)
0	> 250
1	100 - 250
2	50 - 100
3	25 - 50
4	10 - 25
5	5 - 10
6	3 - 5
7	2 - 3
8	1 - 2
9	< 1

UNDULATION SPACING FOR HEIGHT CLASS (2) (6 - 12 inches height)

Class Designator	C-to-C Distance (feet)
0	> 500
1	250 - 500
2	100 - 250
3	50 - 100
4	25 - 50
5	10 - 25
6	5 - 10
7	2 - 5
8	1 - 2
9	< 1

UNDULATION SPACING FOR HEIGHT CLASS (3) (12 - 18 inches height)

Class Designator	C-to-C Distance (feet)
0	> 750
1	500 - 750
2	250 - 500
3	100 - 250
4	50 - 100
5	25 - 50
6	10 - 25
7	5 - 10
8	2 - 5
9	< 2

UNDULATION SPACING FOR HEIGHT CLASS (4) (18 - 24 inches height)

Class Designator	C-to-C Distance (feet)
0	> 1000
1	750 - 1000
2	500 - 750
3	250 - 500
4	100 - 250
5	50 - 100
6	25 - 50
7	10 - 25
8	3 - 10
9	< 3

UNDULATION SPACING FOR HEIGHT CLASS (5) (2 - 5 feet height)

Class Designator	C-to-C Distance (feet)
0	> 2500
1	1000 - 2500
2	500 - 1000
3	250 - 500
4	100 - 250
5	50 - 100
6	25 - 50
7	10 - 25
8	6 - 10
9	< 6

UNDULATION SPACING FOR HEIGHT CLASS (6) (5 - 10 feet height)

Class Designator	C-to-C Distance (feet)
0	> 2500
1	1500 - 2500
2	1000 - 1500
3	500 - 1000
4	250 - 500
5	100 - 250
6	50 - 100
7	25 - 50
8	12 - 25
9	< 12

UNDULATION SPACING FOR HEIGHT CLASS (7) (10 - 25 feet height)

Class Designator	C-to-C Distance (feet)
0	> 2500
1	2000 - 2500
2	1500 - 2000
3	1000 - 1500
4	750 - 1000
5	500 - 750
6	250 - 500
7	100 - 250
8	50 - 100
9	< 50

UNDULATION SPACING FOR HEIGHT CLASS (8) (25 - 50 feet height)

Class Designator	C-to-C Distance (feet)
0	> 2500
1	2000 - 2500
2	1500 - 2000
3	1250 - 1500
4	1000 - 1250
5	750 - 1000
6	500 - 750
7	250 - 500
8	100 - 250
9	< 100

UNDULATION SPACING FOR HEIGHT CLASS (9) (50 - 100 feet height)

Class Designator	C-to-C Distance (feet)
0	> 2500
1	2000 - 2500
2	1750 - 2000
3	1500 - 1750
4	1250 - 1500
5	1000 - 1250
6	750 - 1000
7	500 - 750
8	200 - 500
9	< 200

Table C-5. Matrix III - The Surface Roughness (Obstacles)

OBSTACLE HEIGHT (1st Digit - Matrix III)		OBSTACLE SPACING (2nd Digit - Matrix III)	
Class Designator	Height (Inches or Feet as Indicated)	Class Designator	Edge to Edge Distance (Inches or Feet as Indicated)
0	< 3"	0	> 1000'
1	3" - 5"	1	500' - 1000'
2	5" - 7"	2	100' - 500'
3	7" - 9"	3	50' - 100'
4	9" - 12"	4	25' - 50'
5	12" - 18"	5	10' - 25'
6	18" - 36"	6	3' - 10'
7	3' - 6'	7	1' - 3'
8	6' - 10'	8	6" - 12"
9	> 10'	9	< 6" (Very dense)

Note - The Parameter categories are read: From and including the first number, to but not including the second number (heights and spacings).

Descriptive Subscript Legend

B - Bushes

C - Cultivated Crops

D - Tree Stumps

F - Fence

M - Transient man-made obstructions (Haystacks, etc.)

P - Permanent man-made obstructions (Buildings, Power Lines, etc.)

R - Rocks (Imbedded as opposed to loose)

S - Stones (Loose surface rocks)

G - Grasses

T - Trees

H - Hedges

Table C-6. Matrix IV - Soil Description and Bearing Capacity

SOIL BEARING CAPACITY (1st and 2nd Digits - Matrix IV)		SOIL CLASSIFICATION (3rd and 4th Digits - Matrix IV)	
Class Designator	California Bearing Ratio	Class Designator	Soil Description and Group Symbol (Unified Soil Classification)
00	> 20	00	(GW) Group - Gravel, Sand Mixtures, Well Graded
01	15 - 20	01	(GP) Group - Gravel, Sand Mixtures, Poorly Graded
02	12 - 15	02	(GM) Group - Silt, Sand, Gravel Mixtures
03	10 - 12	03	(GC) Group - Clayey Gravels
04	9 - 10	04	(SW) Group - Well Graded Sands
05	8 - 9	05	(SP) Group - Poorly Graded Sands
06	6.5 - 8	06	(SM) Group - Silty Sands
07	5.5 - 6.5	07	(SC) Group - Clayey Sands
08	4.5 - 5.5	08	(ML) Group - Inorganic Silts
09	3.5 - 4.5	09	(CL) Group - Inorganic Clays
10	2.0 - 3.5	10	(OL) Group - Organic Silts
11	1.5 - 2.0	11	(MH) Group - Inorganic Elastic Silts
12	1.0 - 1.5	12	(CH) Group - Inorganic Clays, High Plasticity
13	0.5 - 1.0	13	(OH) Group - Organic Clay and Silt, High Plasticity
14	< 0.5	14	(Pt) Group - Peat and Highly Organic Soils

Table C-7. Matrix V - Aircraft Trafficability

Type of Aircraft (1st and 2nd Digits - Matrix V)		Trafficability (3rd Digit - Matrix V)	
Class Designator	Aircraft Series	Class Designator	Category Criteria [1]
00	C-7A	0	Safe with landing mat on surface
01	C-47	1	Safe with stabilized soil
02	C-54	2	Remove obstacles
03	C-118	3	Minor grading
04	C-130	4	Major construction effort
05	C-133	5	Divert drainage
06	C-135	6	Unsafe
07	C-141	7	Hazardous weather
08	B-47	8	Prevailing cross-wind
09	B-52	9	Long periods of ice and snow
10	B-58		
11	F-86		
12	F-89		
13	F-100		
14	F-101		
15	F-102		
16	F-104		
17	F-105		
18	F-106		
19	F-4		
20	F-5		

[1] Subscript: Category Criteria of Operations
Full (F) 2000 Coverages
Minimum (M) 700 Coverages
Emergency (E) 40 Coverages
Single Cycle (1 Takeoff and 1 Landing) (S)
Dust

6.2.1 TERRAIN MATRIX DESIGNATOR

The codes of the factors and subclasses by matrix group form the respective matrix group designators. The Simple Terrain Matrix Designator, comprised of the five matrix groups, as illustrated in Figure C-6, indicates the following assumed landing area described in minimum detail as 0311-112-145-0904-035:

Matrix Group I	(Matrix Group Designator: 0311)
Length: 500-6500 ft	(1st and 2nd Digits: 03XX)
Width Slope: 0-2 deg	(3rd Digit: XX1X)
Length Slope: 2-4 deg	(4th Digit: XXX1)
Matrix Group II	(Matrix Group Designator: 112)
Undulation Height: 3-6 in.	(1st Digit: 1XX)
Undulation Slope: 2-4 deg	(2nd Digit: X4X)
Undulation Spacing: 50-100 ft	(3rd Digit: XX2)
Matrix Group III	(Matrix Group Designator: 14S)
Obstacle Height: 3-5 in.	(1st Digit: 1XX)
Obstacle Spacing: 25-50 ft	(2nd Digit: X4X)
Obstacle Type: Loose Stones	(3rd Digit: XXS)
Matrix Group IV	(Matrix Group Designator: 0904)
Soil Type: Inorganic Clay, Type CL	(1st and 2nd Digits: 09XX)
Soil Strength: CBR 9-10	(3rd and 4th Digits: XX04)
Matrix Group V	(Matrix Group Designator: 035)
Type of Aircraft: C-130	(1st and 2nd Digits: 03X)
Trafficability: Operational	(3rd Digit: XX5)

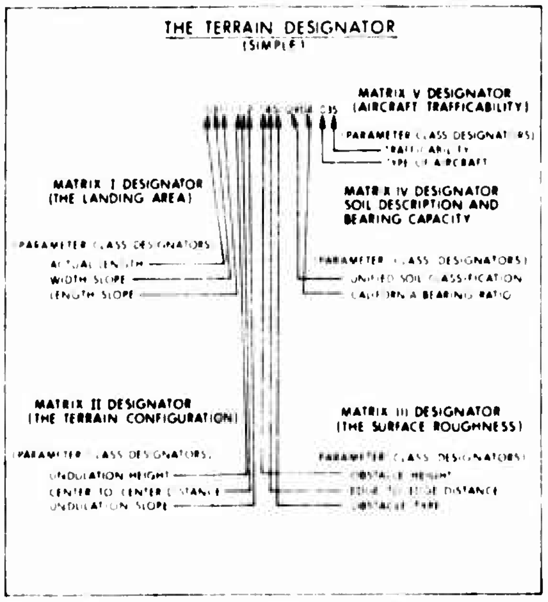


Figure C-6. Simple Terrain Matrix Designator

6.2.1.1 Complex Terrain Matrix Designator

Varying conditions cause the designator to become more complex as additional information is incorporated into the description. Figure C-7 is an example of a more detailed designator that could be applied to the additional data listed below:

$$\frac{0311}{250} - \frac{\begin{matrix}112\\232M\\-598E\end{matrix}}{3} \begin{matrix}14S\\06R\\47B\end{matrix} - \frac{0904}{10} - \frac{035}{65}$$

Matrix Group I

Width Limitation	250 ft	$\frac{1}{250}$

Matrix Group II

Tertiary Undulations (Positive and Negative)
Mound (positive)
6 - 12 in. high, 6 - 10 deg slopes spaced 100-250 ft apart
Erosion Gully (Negative)
2 - 5 ft deep, 60 - 90 deg slope depressions
Spaced 6 - 10 ft apart, and representative width of 3 ft — $\frac{\begin{matrix}232M\\-598E\end{matrix}}{3}$

Matrix Group III

Obstacles (Rocks)
Less than 3 in. and spaced 3 - 10 ft — 06R

Obstacles (Vegetative)
Bushes 9 - 12 in. and spaced 1 - 3 ft — 47B

Matrix Group IV

Soil Moisture	Less than 10 percent	$\frac{1}{10}$

Matrix Group V

Period of Operation
Number of months of year — 6
Subscript for first usable month of operation — 5 — $\frac{1}{65}$

7. MATRIX DESCRIPTION OF REPRESENTATIVE TERRAIN

Two small areas of terrain in Hart County, Kentucky, were selected as examples for the application of the proposed method of quantifying the trafficability characteristics at each location. The first case example described with the aid of an aerial stereophotographic view by a Simple Terrain Designator (0921 705L 94T 0907 035), depicts conditions suitable for landing a C-130 aircraft or smaller. A secondary Matrix V class designator may be added for equivalent vehicular traffic or other uses (Figure C-8).

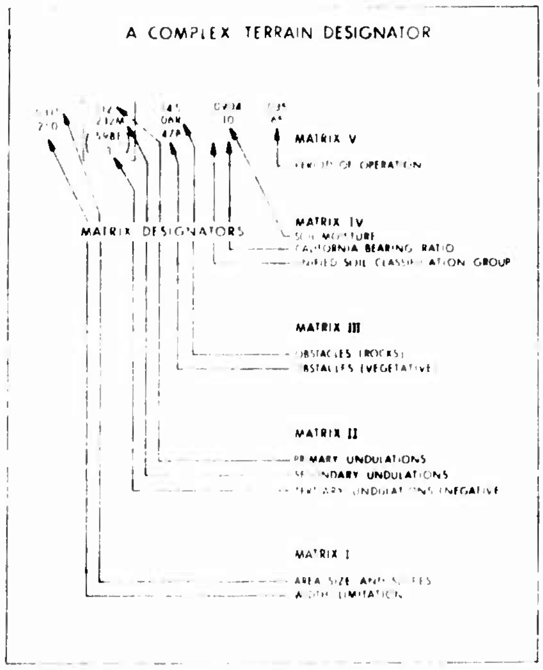
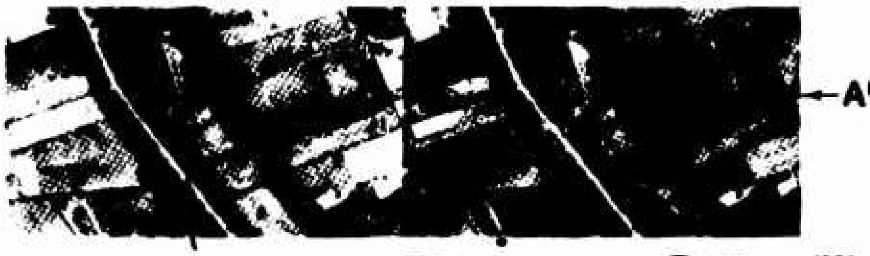


Figure C-7. Complex Terrain Matrix Designator

The second case example, also shown in a similar stereophotographic view, is a Complex Terrain Designator $\frac{0902}{368}$ 717 WC 61T 0906 $\frac{035}{65}$ that describes in more detail the capability of the terrain to support particular categories of aircraft and vehicular traffic (Figure C-9). Topographic cross-section profiles are inserted below each stereopair for ease in visualizing the microrelief along the cross profiles in both areas.

Table C-8 tabulates the many related important trafficability characteristics of Hart County, Kentucky, which includes Areas A and B. They are bearing strength, surface features, vegetation, and hydrology. Climate and weather of the area were classified under the Köppen System; they are: Cfa, which denotes warm temperature climate (C), sufficient precipitation in all months (f), and warmest month mean over 71.6°F or 22°C (a).

The trafficability units of Area A (see Table C-8) are largely 1'a followed by 4' and 2'b in progressively minor occurrence. The units of Area B are 1'a, 1'b, and 2'a in a similar order.



Note undulating valleyed surface in topographic low, and rolling basined surface in topographic highs

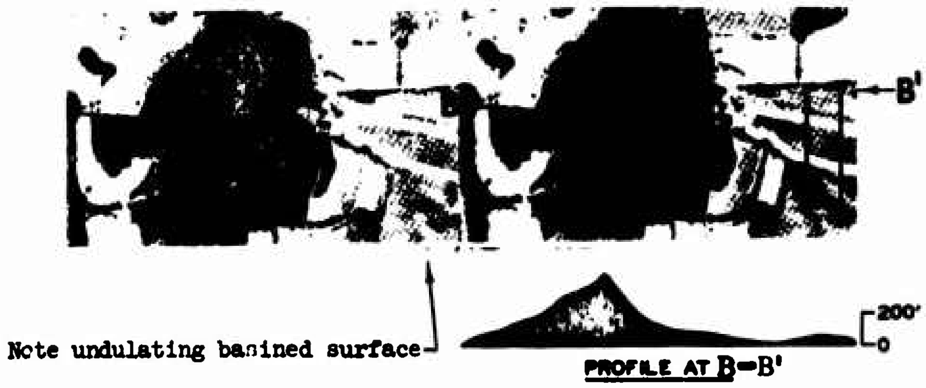
Stereophotography of Valley and Basin Area, Hart County, Kentucky; Scale 1:20,000, Date: 28 August 1958 (Photo is Courtesy of U. S. Army Engineer Waterways Experiment Station, TM 3-331, Report 6, Vol. II)

Terrain Designator (Simple) Area A

[0921 705L 94T 0907 035]

Matrix Group I		
(Length) 10/16"	1050'	09
(Width Slope)°	4 - 6°	2
(Length Slope)°	0 - 2°	1
	(0921)	
Matrix Group II		
(Undulation Height)	20'	7
(Undulation Slope)	0 - 20°	0
(Center to Center Distance)	624'	5
(Undulations Parallel to Length)		L
	(705L)	
Matrix Group III		
(Obstacle Height)	20'	9
(Obstacle Spacing)	25 - 50'	4
Trees	T	
	(94T)	
Matrix Group IV		
(Soil Classification)	CL-ML	09
(Bearing Strength)	Rating Cone Index – 120 CBR Equivalent 5.5 - 6.5	07
	(0907)	
Matrix Group V		
(Type of Aircraft)	C-130	03
(Trafficability)		5
	(035)	

Figure C-8. Terrain Matrix Designator, Area A, Hart County, Kentucky



Stereophotography of Undulating Basin, Hart County, Kentucky;
Scale 1:20,000, Date: 28 August 1958 (Photo is Courtest of U. S. Army Engineer Waterways Experiment Station, TM 3-331, Report 6, Vol.II)

Terrain Designator (Complex) Area B

$$\left[\left(\frac{0902}{368}\right)717WC\ 61T\ 0906\left(\frac{035}{65}\right)\right]$$

Matrix Group I

(Length) 13/16"	1365'	09
(Width Slope)	0 - 2°	0
(Length Slope)	4 - 6	2
Actual Width	368'	
	$\left(\frac{0902}{368}\right)$	

Matrix Group II

(Undulation Height)	20'	7
(Undulation Slope)	2 - 4°	1
(Center to Center Distance)	1/16"-105'	7
W (Undulations Parallel to Width)		
	(717WC)	

Matrix Group III

(Obstacle Height)	10'	6
(Obstacle Spacing)	100' - 500'	1
Trees	T	
	(61T)	

Matrix Group IV

(Soil Classification)	CL-ML	09
(Bearing Strength)	Rating Cone Index — 140	06
	CBR Equivalent 6.5 - 8	
	(0906)	

Matrix Group V

(Type of Aircraft)	C-130	03
(Trafficability)		5
Period of Operation	6 Months	
	Commencing in May	
	$\left(\frac{035}{65}\right)$	

Figure C-9. Terrain Matrix Designator, Area B, Hart County, Kentucky

Table C-8. Terrain Trafficability Characteristics of Areas in Hart County, Kentucky

Region 1/	Rating Cone Index*		Slopes, %		Surface Characteristics**			Traverse† in miles	"Stepped" Surface	Trees††	Shrubs‡	Hydrographic Characteristics‡‡
	Topographic Highs	Topographic Lows	Characteristic	Maximum	Ditches	Cut and Fill Banks	Gullies					
1'a	125	125	<20	50	a	b	d	0.4	e	D	C	2
1'b	125	125	<20	50	c	c	d	0.5	c	B	B	2
2'a	120	120	<30	100	b	b	d	0.3	e	C	C	2
2'b	120	120	<50	100	c	c	d	0.4	a	B	B	1
3'a	140	45	<30	60	b	b	b	0.3	d	C	C	2
3'b	140	45	<40	60	c	c	c	0.4	a	A	B	1
4'	60	35	<5	60	d	d	d	0.7	e	C	C	3
5'	140	45	<30	60	b	b	b	0.4	e	C	C	2
6'	300+	300+	<5	15	a	a	e	0.1	b ∫	C	C	1

* The RCI given is the minimum probable value during the wet season; correlate with California Bearing Ratio Equivalent

** These features must, in general, include slopes greater than 1 ft in height and steeper than 60%. The scale of value is as follows:

- a: Numerous.
- b: Common.
- c: Present, but not common.
- d: Rare.
- e: Absent.

† Mean distance in miles between gullies, ditches, or cut and fill banks along a random straight line.

†† The scale of values for tree density is:

- A: Dense; passable, but path tortuous.
- B: Moderately dense; passable, but path length substantially extended.
- C: Patches and rows; path length slightly extended.
- D: Rare or absent; no appreciable effect on path length.

‡ The scale of values for shrub density is:

- A: Dense; visibility seriously inhibited; path selection difficult.
- B: Moderately dense; visibility somewhat inhibited; path selection not seriously inhibited.
- C: Rare or absent; visibility not appreciably affected; path selection easy.

‡‡ The scale of values for hydrographic features is:

- 1: Surface water absent.
- 2: Small ponds, easily bypassed.
- 3: Unfordable water barrier subdivides region.

∫ Curbs, terraces, walls, etc.

1/ Area A 1'a, 4', 2'b; Area B 1'a, 1'b, and 2'a

8. MATRIX DATA FROM LIBRARY SYSTEM OF ANNOTATED REMOTE SENSING IMAGERY

A system of recording, indexing, and storing information for rapid and efficient retrieval by an analyst is most advantageous in the development of a complete matrix designator of terrain.

Basic recording techniques can serve other military applications such as site selection, if reliable data are stored and properly indexed. The data storage could be on punched or marked cards or in folders, handbooks, or folios.

The indexing of a terrain environment would include all the terrain factors and related information by location, subject, photography, maps, reports, and other sources of data related to the specific problem. Refer to the report, "Handbook for Producing a Folder for a Library of Annotated Aerial Photographs", by H. T. Leibowitz, University of Oxford, December 1966 (AD 814 934) for comprehensive recording procedures that can provide other types of useful data to supplement a terrain matrix designator.

APPENDIX D

Optimum Remote Sensing System

The designation of an optimum remote sensing system for determining, measuring, and monitoring natural terrain properties and conditions depends on its proposed applications and on available resources for system development. Many surveys and feasibility studies have been made, and tabulations prepared, regarding the capabilities of various sensors, either singly or grouped, to obtain the necessary data. In actual usage problems of weight and volume, power requirements, mutual interference, and output format must be carefully considered.

It is generally recognized that photography is the most useful sensor system, as its output is most familiar to the human senses and its interpretation has been most highly developed. Extending to either side of the narrow visible and photographic wavelengths of the electromagnetic spectrum are ultraviolet and infrared, both of which can be used to record valuable data. The existence of "atmospheric windows", permitting the transmission and recording of longer wavelength infrared energy, makes the use of infrared scanners very profitable.

Further into the microwave region of the spectrum, the use of passive microwave radiometry and active or passive radar (both imaging and non-imaging) becomes of value. Radar imagery can reveal much information regarding geologic formations and both surface and sub-surface earth properties, and its interpretation is fairly well developed in the geoscience community. Radar altimeters in particular are of value in studies of the regional relief or topography of the earth's surface.

At the opposite end of the spectrum, gamma-ray sensing is used in mineral exploration and shows much promise for determination of soil type and moisture content. Airborne use of this technique requires low-level surveys and quite large arrays of detectors.

The natural force fields of gravity and magnetism also offer clues as to the existence and extent of geologic materials and subsurface conditions. Airborne use of these techniques is quite standard, and data interpretation is well developed.

Droppable sensors for determining soil properties such as strength are well developed, and the Sandia Corporation's use of deep-penetrating projectiles is an advanced technique worthy of use in an optimum sensing system.

The recent development of lasers has a most useful application in very-high-resolution airborne profile recorders for measuring microrelief within 12 in. of accuracy. Studies of laser reflection "signatures" on rock and soil material are underway, which ultimately should permit material identification and discrimination.

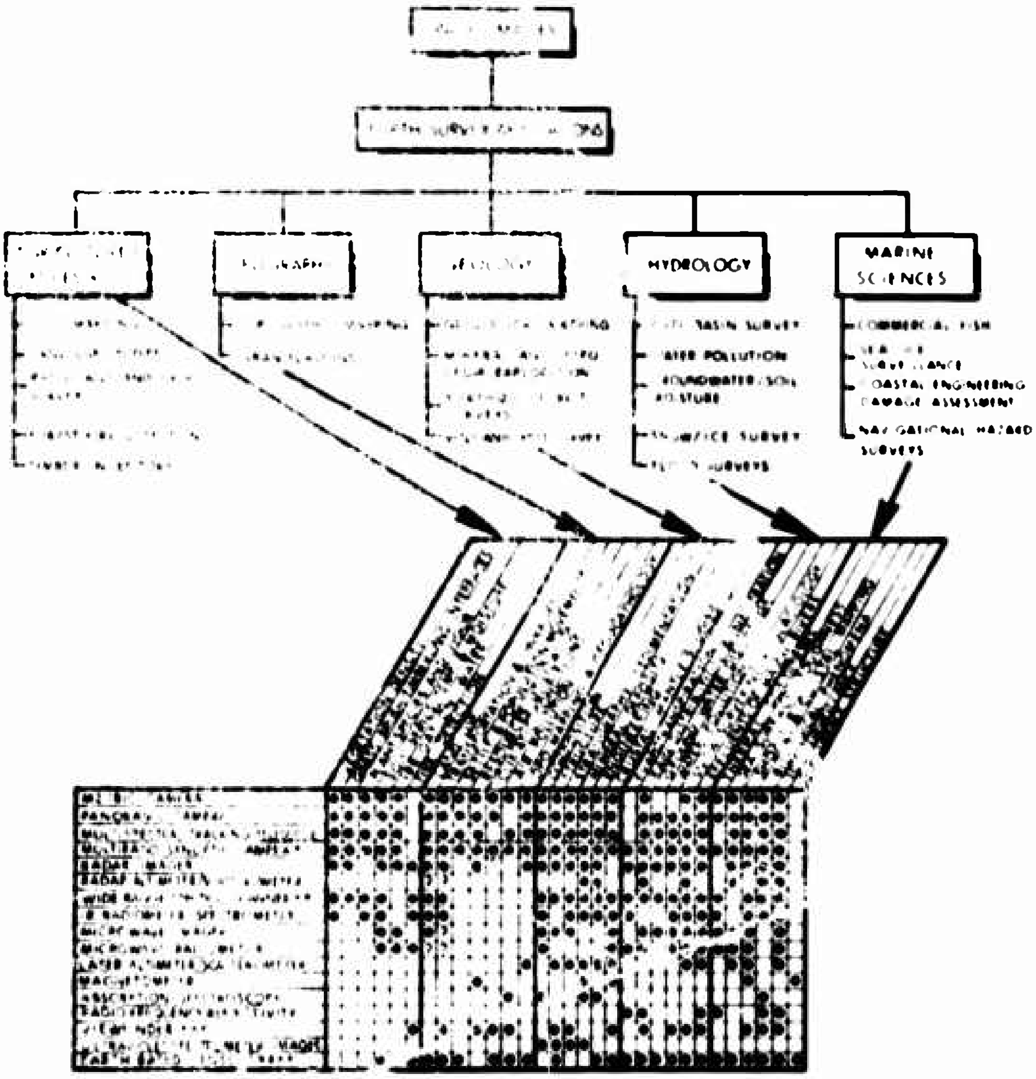
Figure D-1, prepared for NASA purposes, presents an overall view of sensors that have varied uses in the earth sciences. The resolution of sensors at spacecraft altitudes is necessarily less than at aircraft altitudes, but the sensors can obtain some useful geophysical data.

In general, an optimum system should contain a metric or mapping camera using standard black and white film to obtain an overall view of the terrain being surveyed; a panoramic camera to extend the view of the area to include surrounding terrain; a multispectral camera system to exploit the spectral reflectance signatures of terrain material; and other mapping cameras simultaneously recording data on color and infrared films. An additional camera using ultraviolet sensitive film would be a valuable additional source of data for experimental studies. Spectrally filtered photometers bore-sighted with the cameras would also be desirable.

Three optical-mechanical scanners are considered necessary in an optimum system. Two of these should operate in the 3 to 5 μ and 8 to 14 μ infrared regions, respectively, and the other should provide multi-wavelength scanning throughout the visible spectrum.

A high-resolution, side-looking, imaging radar, a radar scatterometer, (Moore, 1966) a long-wavelength radar, a laser altimeter, and an all sweeping-frequency radar should provide both surface and sub-surface data.

A passive microwave imager with a multi-frequency microwave radiometer having dual-polarization capability would provide additional data.



* [illegible] RETURN AND TELEMETRY MODES

** [illegible] 0 MICRONS

*** THIS INSTRUMENT AUGMENTS AN ASTRONAUT'S VISION WITH OPTICAL POWER AND DIRECTIONAL DATA. THE ASTRONAUT CAN UTILIZE THE VIEWFINDER BY ITSELF OR IN CONJUNCTION WITH OTHER DIRECTIONAL TYPE SENSORS

**** THESE EARTH BASED SENSORS MAY INCLUDE A NUMBER OF FIXED AND MOBILE INSTRUMENTS, SUCH AS BUOYS, SEISMOGRAPHS, STREAM GAUGES, AND SO FORTH, PLACED ON OR NEAR THE EARTH'S SURFACE FOR DETECTING, RECORDING, AND TRANSMITTING A VARIETY OF EARTH RESOURCES PHENOMENA OF INTEREST TO A LARGE NUMBER OF USERS

THIS TABLE HAS BEEN SUMMARIZED FROM MORE DETAILED TABLES FOR EACH DISCIPLINE AND, THEREFORE, DOES NOT INCLUDE ALL THE ANTICIPATED APPLICATIONS WHICH HAVE BEEN IDENTIFIED TO DATE

Figure D-1. Potential Applications for Earth Orbital and Airborne Scientific Data

An airborne magnetometer and airborne gravimeter would acquire useful supplementary information on the existence of geologic conditions revealed in the force field anomalies. Airborne electromagnetic sensors would detect changes in conductivity or the dielectric constant associated with variations of sub-surface formations.

An array of gamma-ray detectors and scintillometers is needed to enhance the measurement of soil types and their extent and to provide needed data on mineral deposits.

A capability to airdrop contact sensors should be part of an airborne system, as well as an extensive telemetry recording capability to obtain supplementary "ground truth" data.

Inherent in all the above discussion is the necessity for precise navigation of the aircraft carrying the remote sensing system, the existence of suitable view-finders and driftmeters for photographic positioning control, and an overall time-marking system for precisely coordinating all navigation data, sensor out-puts, and events. On-board processing of film, for at least test strips, is seen as valuable but not mandatory.

The various sensors have widely diverse output formats, such as film recording, strip charts, tape records, and telemetry voltages. Digitizing as much as possible of the output format and recording the signal on multi-channel tape recorders is seen as a feasible present approach. In the future, the development of automated, real-time, photo-processing and recording of data by flying-spot scanners and densitometers should enable the consolidation of all sensor outputs and a computer correlation with known pattern recognition techniques into near-real-time presentation. A digitized total "terrain data bank" stored in a ground computer station could provide quantitative values of terrain factors such as type, slope, moisture, temperature, etc., for any required application from such digitized interpretive processes shown in Figure D-2 and in Figure 31 of the report.

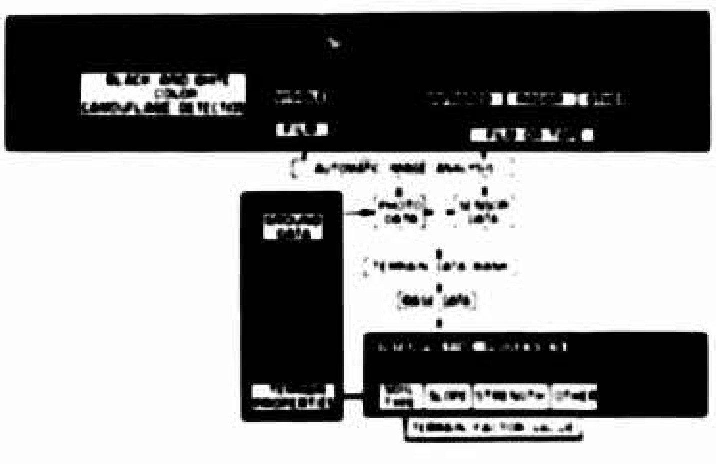


Figure D-2. Optimum Terrain Analysis by Orbital and Airborne (Non-Contact), Ground (Contact), and Intuitive (Indirect) Methods

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13. ABSTRACT

A survey of the state-of-the-art in the evaluation of natural terrain by earth-science techniques and measurement systems is presented in response to a need that existed for many years. This report considers the terrain as an envelope of the environment and all related parameters that are basic in an evaluation for relevant military applications such as unimproved landing areas, trafficability, site selection for operational facilities, terrain reconnaissance and surveillance, and target detection within a masked terrain complex. Methods of terrain-data acquisition, analysis, and evaluation and their limitations are reviewed. The status of research and development, specifying the gaps in technology, is summarized with accompanying conclusions. The report forecasts the requirement for an automated terrain-data acquisition, storage, and display system. Recommendations are suggested for further investigation to advance technology that will provide quantitative terrain factor values. A simplified matrix method of digitizing terrain data is described in the appendix as a necessary intermediate step to the computerization of pertinent data. Information pertaining to the classification of terrain data, field devices to measure bearing strength, and a visualized optimum remote sensing system is also given in the appendix. A glossary and a comprehensive bibliography are included.

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Bearing Strength						
Climatology						
Data Acquisition and Processing						
Earth Sciences						
Geography						
Geology						
Geophysics						
Hydrology						
Landforms						
Mapping						
Military Construction						
Military Geographic Information						
Physiography						
Remote Sensing						
Research and Development						
Rocks						
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Terrain						
Terrain Analysis						
Terrain Applications						
Terrain Classification						
Terrain Factors						
Terrain Matrix						
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